NATURAL LIGHTING IN MEDITERRANEAN CLIMATES

VISUAL COMFORT IN TOP-LIT SPORTS HALLS: FROM THE BARCELONA 1992 OLYMPICS TO THE TARRAGONA 2018 MEDITERRANEAN GAMES

MARÍA LEANDRA GONZÁLEZ MATTERSON

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Front cover:

Luz difusa

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Doctoral thesis by:
Maria Leandra González Matterson

Thesis advisor:
Joan Lluis Zamora i Mestre

Department of Architecture Technology (TA)

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Doctoral thesis by

María Leandra González Matterson

Thesis advisor

Prof. Joan Lluis Zamora i Mestre

Programme Coordinator

Prof. Helena Coch i Roura

Programa de Doctorat en Arquitectura, Energia i Medi Ambient

PhD. program in Architecture, Energy and Environment

Departament de Tecnologia de l'Arquitectura – TA

Department of Architectural Technology -TA

Universitat Politècnica de Catalunya – UPC

Barcelona Tech

Barcelona, November of 2020

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ABSTRACT

The role of natural light in the health and wellbeing of users is a central subject to architectural design today. Sustainability and energy efficiency are also leading concerns. Therefore, new and existing buildings must provide optimal comfort, while reducing the energy consumption for lighting, ventilation and heating.

In this context, this thesis investigates the performance of natural light in sports halls in a Mediterranean climate in relation to both users, athletes and spectators, and television broadcasting requirements. In addition, it explores the impact of daylight design strategies to achieve visual comfort.

Even though there is a large amount of research in the field of visual comfort and daylight, sports spaces are scarcely studied. Because the athletes and their visual targets are in movement, the visual field becomes three-dimensional and its assessment complex. Thus, this thesis explains a specific methodology which was designed and implemented from an architectonic and holistic approach. Both qualitative and quantitative parameters of visual comfort were assessed in daylit sports halls. Objective and subjective data were collected from case studies, comprising in-situ measurements, such as horizontal and vertical illuminance. As well, it included high dynamic range images survey, glare and contrast evaluation in the field of view, simulations, an experimental test and visual comfort surveys. In addition, it analysed the optimisation of daylight at the initial stages of the design development of a new sports facility.

This research is explained in three main parts completed over several years. The first part of this work evaluates the performance of naturally lit and, in particular, top-lit sports halls built for the Barcelona 1992 Olympic Games. Thirteen different sport buildings in Catalunya were assessed, where the widespread use of skylights for daylighting correlates with a suitable global performance. Nonetheless, visual discomfort issues by absolute and contrast glare were frequent because of lack of daylight control and solar protection devices, among others.

In the second part and based on previous results, daylight design strategies are suggested for the improvement of visual comfort in four of the Olympic sports halls. Photorealistic and calibrated images were obtained to validate the design measures proposed through experimental tests. Additionally, the panel responses were collected and analysed, revealing that users prefer a uniformly well day-lit court, when daylighting strategies were integrated. The court is featured as the main and central element of the luminous space for users.

The third part was completed at the Catalonia Institute for Energy Research - IREC and presents daylighting design strategies, which were compiled for the optimisation of natural light in sports halls of Catalonia. These guidelines were implemented in the building design of the new Palau d'Esports Catalunya, built for the Tarragona 2018 Mediterranean Games. The goals of the optimisation of the central skylight were also contrasted and verified with two Post Occupancy Evaluation campaigns.

Finally, this work highlights the complexity of the design of the luminous space and encourages the inclusion of natural light from early design phases. This can be useful either for retrofitting strategies or new design of sports halls in Mediterranean climates and other climates and latitudes, since both overcast skies and clear skies were assessed.

Key words: natural light, daylighting, sports halls architecture, toplighting, visual comfort, glare, Mediterranean climate

RESUMEN

El rol de la luz natural en la salud y el bienestar de los usuarios es un tema central del diseño arquitectónico actual. La sostenibilidad y la eficiencia energética son también aspectos a considerar. Por lo tanto, los edificios nuevos, así como los existentes, deben proporcionar condiciones óptimas de confort mientras se reduce la demanda de energía para iluminación, ventilación y calefacción.

En este contexto, esta tesis investiga el desempeño de la luz natural en los pabellones deportivos en un clima mediterráneo, en relación tanto con los usuarios, atletas y espectadores, como con los requerimientos para la retransmisión televisiva. Además, explora el impacto de las estrategias de diseño de iluminación natural para lograr el confort visual.

Aunque hay gran cantidad de investigación en el campo del confort visual y la luz natural, los espacios deportivos están menos estudiados. Debido a que los atletas y sus objetivos visuales están en movimiento, el campo visual se vuelve tridimensional y su evaluación es compleja. Por ello, en esta tesis se aplica una metodología específica, que se diseñó e implementó desde un enfoque arquitectónico y abarcador. Se evaluaron parámetros cualitativos y cuantitativos del confort visual en pabellones deportivos con iluminación natural. Se obtuvieron datos objetivos y subjetivos de casos de estudio, por medio de mediciones in-situ, como la iluminancia horizontal y vertical. Asimismo, se obtuvieron imágenes de rango dinámico ampliado y se realizaron: la evaluación de contraste y deslumbramiento en el campo visual, un test experimental y encuestas de confort visual. Además, se analizó la optimización de luz natural en las etapas iniciales del proyecto de diseño en una nueva instalación deportiva.

Esta investigación se desarrolla en tres partes principales, completadas en varios años. La primera parte de este trabajo evalúa el rendimiento de los pabellones deportivos con iluminación natural, y en particular con iluminación cenital, construidos para los Juegos Olímpicos de Barcelona 1992. Se evaluaron trece edificios deportivos en Catalunya, donde se correlaciona, en general, el uso extendido de lucernarios y claraboyas para iluminación natural y un rendimiento adecuado. Sin embargo, las situaciones de disconfort visual por deslumbramiento absoluto y por adaptación son frecuentes. Esto es debido a la falta de control de la luz natural y sistemas de protección solar, entre otros.

En la segunda parte, y en base a los resultados obtenidos, se sugieren estrategias de diseño para optimizar la luz natural y mejorar el confort visual. La pista deportiva se presenta como el elemento principal y central del espacio luminoso para los usuarios.

La tercera parte se realizó en el Institut de Recerca en Energía de Catalunya – IREC, donde se compilaron y presentaron estrategias de diseño para la optimización de la luz natural en los pabellones deportivos de Cataluña. Estas recomendaciones fueron implementadas en el diseño del nuevo Palau d'Esports Catalunya, construido para los Juegos Mediterráneos de Tarragona 2018. Los objetivos de optimización de la claraboya central también se contrastaron y verificaron con dos campañas de evaluación post-ocupación.

Finalmente, este trabajo destaca la complejidad del diseño del espacio luminoso y promueve la inclusión de la luz natural desde las primeras fases de diseño. Esto puede ser útil en ambos casos, para estrategias de rehabilitación o para nuevos proyectos de pabellones deportivos en climas mediterráneos, así como también para otros climas y latitudes, ya que se evaluaron cielos nublados y cielos despejados.

Palabras clave: luz natural, iluminación natural, arquitectura deportiva, iluminación cenital, confort visual, deslumbramiento, clima mediterráneo

Note to the reader:

To my son,

to my parents.

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GENERAL INDEX

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1st Part - Visual comfort in top-lit sports halls of the Barcelona 1992 Olympic Games

2nd Part - Assessment of daylighting design strategies to improve visual comfort in sports halls using simulations and experimental test

1

Introduction

This chapter presents an overview of the research work carried out and summarizes the main topics covered by this study. Key factors are presented to understand the opportunities and challenges from an architectural approach, to achieve visual comfort in daylit and top-lit sports halls in Mediterranean climates. The main hypothesis is if daylight, in particular with toplighting could contribute to the visual comfort in sports halls in a Mediterranean climate. In addition, the specific methodology designed to demonstrate the hypothesis and the structure of the research work are explained.

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1.1 Context

Architecture was predominantly concerned for centuries, among other things, to bring more daylight to building interiors by creating strategic and carefully placed openings. Natural light was the only efficient source available. Nowadays, efficient artificial light and technology have freed designers from these restraints (Ruck et al. 2000, p2-1).

In the last decades, there has been an increasing attention on the provision of optimal comfort conditions for users, while reducing the energy demand in new and existing buildings for indoor conditioning: lighting, ventilation and heating.

The benefits of the visible and non-visible effects of natural light have also been highlighted in recent years. For example, the basic needs of natural light for human health and wellbeing and the vital regulation of the human circadian metabolism, among many advantages.

The sports practice in indoor spaces requires the achievement of environmental comfort conditions, and in this particular case, there are minimum lighting requirements for visual comfort.

Sports competitions must fulfil highest levels of quality and quantity of lighting for different users: athletes, spectators and massive audiences of remote spectators, including TV broadcasting requirements. This adds extra complexity to provide visual comfort conditions for a mixture of users.

1.2 Problem statement

The use of natural resources in buildings could contribute to the achievement of optimal levels of environmental comfort in temperate climates, for example natural light, winter solar gains and natural ventilation. These can also contribute to users' well-being and improving the building's behaviour with potential energy savings.

Buildings designed to respond to the sun and natural light have to consider many factors, such as climate and latitude, which define sun altitude and solar radiation, the site and the urban context, defining external obstructions and reflections (Fontoynont et al. 2004).

The architectural design and the implementation of daylight strategies in buildings requires a series of considerations to ensure the visual comfort for users. The building orientation, shape and urban context are significant to define direct, diffuse, reflected interior and exterior light components. The choice and the proportion of fenestration by toplighting and sidelighting are also defining the users' perception and their interaction with the space itself as the luminous environment (López- Besora and Coch 2017).

Natural light availability in Mediterranean climates

Different from Northern climates, there is a high natural light available in Mediterranean climates, as is the case of Barcelona at latitude 41°38' North. It is also characterized by a higher proportion of clear skies and high solar radiation levels, see Figure 1-1, Figure 1-2 and Figure 1-3.

This availability of daylight can contribute to achieve naturally lit buildings. In particular, in sports halls it could provide minimum illuminance levels through design strategies, but requires solar protection and daylight control.

Figure 1-1. Images of natural light in Mediterranean cities: Tunisia, Latitude 36° N.

Solar devices in windows' house in Sidi Bu Said, left. Courtyards and porticoes of the Great Mosque, Sousse, centre. Commercial street with pergolas in Sidi Bu Said, right.

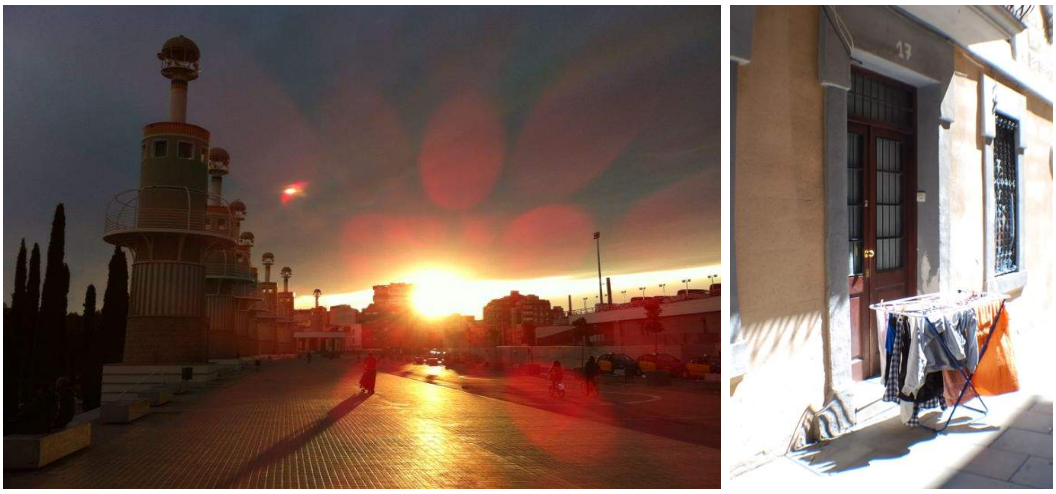

Figure 1-2. Images of natural light in Mediterranean cities: Barcelona, Latitude: 41°38' N.

The sunset in l'Espanya Industrial Park, Sants, left. Drying clothes at noon in the street, Barceloneta, right.

Figure 1-3. Images of Mediterranean cities: Barcelona, Latitude: 41°38' N.

Housing building in Barceloneta (Coderch, J.A and Valls, M. arch. 1951-1955) with Mediterranean blinds as the sun-shading devices, left. Maritime front with balconies and overhangs, right.

Mediterranean climates are characterized by high solar radiation levels and blue skies during the summer. Consequently, examples of vernacular architecture show intermediate spaces, white or light exterior surfaces, small openings and solar shading devices, as the Mediterranean blinds, to control natural light and solar gains.

Natural light in buildings

One of the major advantages of integrating daylighting in buildings is that it offers a physical connection between occupants and the exterior world. Through daylighting users can have - in a quick look from indoors - the sense of time, weather and safety conditions, views and landmarks, sense of place and orientation. Likewise, it is the regulation of the human circadian metabolism, which is one of the major benefits of daylight to the human health and wellbeing but less evident.

Daylighting systems

The use of daylighting in architecture or daylighting strategies have different purposes, see Figure 1-4, Figure 1-5 and Figure 1-6, according with the type of building, and can be divided in two main categories: top-lit and side-lit.

The toplighting systems admit more daylight per square meter of glazing than vertical windows, e.g.: skylights and roof lights (Hopkinson and Kay 1972), see Figure 1-7 and Figure 1-8. Furthermore, in overcast conditions the light could be uniformly distributed throughout the space and glare might be efficiently controlled by translucent glazing (Fontoynont et al. 2004).

However, unsuitable design solutions and techniques in the construction of toplighting systems, concerning climate-based conditions and specific functions of buildings have led to the simplification of discarding these systems. Toplighting could be considered uneconomical and not feasible (Lawrence and Roth 2008), especially in places with high natural light availability. Examples of barriers to implementing toplighting are due to costs versus energy benefits and inadequate knowledge, that could lead to faulty design and concerns about leaks and operation. Other barriers are related to avoid excessive heat gains by radiation, glare in critical areas or spaces during the visual task and the maintenance and operation of control elements, including sun shading devices (Lawrence and Roth 2008, p.3-5). Those issues have led, in most cases, to disable daylighting systems permanently.

On the contrary, sidelighting systems are very common and highly valued in buildings, such as windows. This is mainly because windows offer outdoor views, a very good connection to users with the natural or built environment, through the long and short outside views from inside. However, glare, personalised control and the regulation of daylight could be recurrent issues in different types of buildings such as offices, schools and sports halls.

User interaction with the sports hall space

Sports halls are built to allow users to practice sports or watch sport events indoors and in controlled and safe environments. Accordingly, the sports hall users can be divided into three main categories: athletes or players (including coaches, judges, officials, referees, linesmen, etc.), spectators and remote spectators, including TV broadcasting. There are also other activities that happen in these buildings, which are related or not to sports, such as community gatherings, arts or entertainment performances. In most sports, the athlete or player is interacting with the space, moving and more or less active while they are tracking objects and players in movement too. The spectator is generally static in relation to their position in space, but the action in the court is also followed, tracking objects and players in motion around the space. The athletes' visual task and their interaction with space is dynamic, while for spectators and TV broadcasting the visual task is dynamic in the same way, but their position in relation with the space could be both static and dynamic.

Figure 1-4. Images of buildings with different daylighting design strategies in Catalunya.

German pavilion in Barcelona (Mies Van der Rohe 1929), left. L'Atlàntida theatre and music school in Vic (Josep Llinàs, 2010), centre. The Palau de la Música Catalana, Barcelona (Lluis Domènech i Montaner, 1905-1908), right.

Architectural elements and coating properties, as colour, reflectance factor, shape and position in the space, are used in indoors and outdoors to create lighting effects: contrast, specular and diffuse daylight reflections.

Figure 1-5. Images showing splayed windows and colourful glass, to improve the daylight diffusion and distribution.

La Chapelle de Notre-Dame du Haût in Ronchamp in France (Le Corbusier, 1955): detail of window, left, and part of the south wall, right. The splayed surfaces are used to avoid hard frames and sharp intersections between the wall and glazing surfaces.

The south wall of Notre Dame du Haut in Ronchamp by Le Corbusier, is one of the most fascinating designs with daylight. Different shapes, disposition of the glass in relation with the thickness of the wall, partition, position of glazing materials and colours of windows are used to create a unique and prodigious visual experience from indoors.

Figure 1-6. Indoor and outdoor views of sidelighting with strategies to decrease excessive contrast (Source: https://miromallorca.com/es/fundacion/arquitectura/moneo/).

Moneo building of Fundació Pilar i Joan Miró in Mallorca, ES (Moneo, R., 1992): low windows and clerestories with shielded openings, splayed surfaces, translucent glazing and external white louvres or brisoleils.

1.2.1 Toplighting systems

Despite these facts described above, daylighting and toplighting systems are still currently implemented in buildings, and in particular in sports halls and Olympics buildings. Examples of sports halls built and actually "in use" are numerous, e.g. the 1992 Olympics Games in Barcelona, see Figure 1-9.

However, few references have been found with regards to the use of natural light, in particular by toplighting and their implications to the users' visual comfort in sports architecture in middle latitudes.

Moreover, the daylighting systems are complemented with the interior architecture which plays a main role, such as defining the overall luminous ambiance or scene perceived by users, e.g.: through a diffuser and/or reflective material, cold, warm, dark and bright colours. Additionally, the proportion of toplighting and sidelighting systems implemented varies in each building, which also modifies the luminous environment and user perception.

1.2.2 Visual comfort in sports halls

The work plane for users of sports halls is dynamic and their visual field or field of view - FOV becomes three-dimensional. This is because users and their visual task are in motion. Several simultaneous work planes must be considered for the sports hall users, such as athletes, spectators/remote spectators and TV broadcasting requirements, see Figure 1-10.

From a comprehensive point of view, sports hall spaces are complex spaces to assess under natural light conditions. It is mostly because visual users' requirements and multiple view directions must be considered. It requires the use of a combination of tools and experimental methods to reach a comprehensive study.

1.2.3 Illuminance levels requirements

The lighting levels and the luminous environment in sports hall have different requirements and configurations according to training, local, regional, and international competition levels of play, including conditions for TV broadcasting. Furthermore, the surfaces' colours, daylighting and artificial lighting levels could be modified for competition purposes. As a consequence of that, the luminance distribution could be noticeably changed, see Figure 1-11.

Sometimes, daylight cannot accomplish these requirements due to the architecture itself, as the building shape, orientation, implementation of daylighting system, and the external factors as the daylight variability throughout the day and year, sky conditions: overcast and clear skies, and external obstructions.

Sports halls architecture

From the architectonic point of view, in sport halls facilities there are wide-ranging design solutions depending on the type of sport, spectator's capacity, site, level of play (competition, training, leisure and other activities), among others. In this sense, all the architectonic elements in the space shape-up the luminous environment or the "scene" perceived by users, such as floors, side walls, ceiling, fenestrations, structure and roof. Furthermore, the design of toplighting and sidelighting systems are not standard, resulting in an extensive range of implemented technical solutions, as shown in examples of Figure 1-9.

Figure 1-7. Images of the diverse top-lit spaces in museum buildings in high latitudes.

The British Museum in London Lat: 51°51′ N, left. Le Louvre Museum in Paris Lat: 48°86′ N, centre. The Pergamon Museum in Berlin, Lat: 52°30′ N, right.

Figure 1-8. Images showing examples of top-lit spaces in contemporary architecture, new projects and extensions.

The Terminal 4, International Airport in Madrid Lat: 40°41′ N, left. Le Louvre Museum in Paris, Lat: 48°86′ N, centre. Museu d'Historia de Catalunya in Barcelona Lat: 41°38′ N, right.

Figure 1-9. Images of the diverse day-lit sport halls in Catalunya.

CEM L'Espanya Industrial- CEM EI (05/02/2008 12:10 pm, clear sky), left. Palau Blau Grana FC Barcelona- PBGFCB (20/02/2008 11:00 am, overcast sky), centre. Pavelló Municipal Girona Fontajau- PMGF in Girona (22/05/2007 1:15 pm, clear sky), right.

1.3 Background

The functional and objective approach in the use of natural light and toplighting in buildings has been less covered in the existing bibliography. In general, it has produced profuse results about the ludic or symbolic use of the overhead or top-light in architecture (Lam 1977; Torres Tur 2005).

Furthermore, bibliographic references are limited when concerning the toplighting and their performance in Mediterranean climates. At these latitudes, with high levels of solar and natural light availability, there are other important considerations in relation to natural and artificial conditioning. Of these, solar gains and glare in relation with the thermal and visual comfort in buildings are main concerns (Paricio 2001; López-Besora et al. 2016).

With respect to the objective assessment of the users' visual comfort in daylight conditions, they are largely studied around the world. The emphasis of many studies done in offices, schools, factories and industry buildings is on the working plane. Accordingly, metrics and parameters as horizontal E_h, vertical E_v illuminance and luminance L are mainly used, where both user and the user's point of view are static (Fontoynont 1999; Baker, Fanchiotti and Steemers 2003). For example, there are numerous studies performed in offices which have originated the most common parameters to define the visual comfort indexes under daylight, as the Daylight Glare Probability- DGP (Wienold 2006). However, the studies of users' visual comfort in other types of buildings in Mediterranean Climates are less numerous but specific (López-Besora 2015; Uriarte Otazua 2016).

Studies about daylighting in sports architecture at high latitudes and cold climates have been found, as in the case of Scotland (Sports Scotland 2016), in Norway (Ding 2017) and in Netherlands (Veugelers 2017a; 2017b). There is a large number of constructed sports hall buildings in middle latitudes, although there is no analytical data available and linked to daylighting and visual comfort.

1.4 Opportunities and challenges

Performing a comprehensive and functional assessment of the use of daylighting systems in sports halls in Mediterranean climates faced both opportunities and challenges.

The opportunities are related to the type of building, the sports halls, the daylight availability, see points 1.2, pp. 3, and the current and mandatory requirement for the daylight optimization in sports facilities in Catalonia.

From the methodological approach, the main challenges of this research work are related to the following issues:

- The dynamics of natural light and their performance in existing and in-use buildings
- The assessment of the users' visual comfort and their visual perception in sports halls, while users perform a dynamic visual task
- Different requirements, in terms of visual comfort and lighting levels considering users and levels of play: training, regional, national and international competitions, including TV broadcasting
- The sports hall architecture and daylighting, both defining a complex luminous environment

Figure 1-10. Images of sports halls in Barcelona, with natural and artificial light.

Competition and TV broadcasting conditions in the INEFC M (17/02/2008 1:05 pm, overcast sky), left. Training conditions in the CEM Olímpics Vall d'Hebron - CEM VH (15/10/2009, intermediate sky), right.

Figure 1-11. Images of the top-lit court of the INEFC sports hall in Barcelona.

Training conditions in the INEFC M building (6/02/2008 1:05 pm, clear sky), left. International Fencing Competition with TV broadcasting in the INEFC M (17/02/2008 1:05 pm, overcast sky), right.

Figure 1-12. Images of top-lit and side-lit Olympic sports halls in Barcelona.

Palau d'Esports de Granollers-PEG (20/02/2008 12:50 pm, overcast sky), left. CEM VH (8/11/2008 2:00 pm, overcast sky), centre; and Palau St Jordi- PSJ (17/01/2008 12:20 pm, clear sky), right.

In multisport halls, there are different sports' activities, users as athletes, spectators, remote spectators or TV broadcasting, levels of play, such as training, regional, international competitions. As well, diverse solutions and materialization for daylight systems.

Natural light dynamics

The main characteristic of natural light is that it is dynamic, both in terms of intensity, spectrum and direction. Natural light constantly changes during the day, seasons and year. Thus, day-lit environments vary in the same way.

Dynamic visual task assessment

In the case of sports hall architecture, the assessment of the visual field is complex because users and their visual task are in movement. Moreover, there are multiple view directions or virtual work planes defined by sports users. For example, athlete´s visual task is linked to the sports practice and level of play. Among others, it also depends on the athlete's position in the space and the requirements for tracking objects in terms of speed and trajectory, see Figure 1-14 and Figure 1-15.

Visual perception

The visual perception is a subjective process that is strongly related to the user interaction with the physical environment and light, see Figure 1-17. It's also related to many other factors, including user characteristics as age, gender, if visual impairments are affecting them, expectations, duration of the activity and visual task, as examples.

In this sense, qualitative and user perception issues are more complex than the assessment of illuminance levels in a horizontal working plane, which require the use of more comprehensive techniques and the use of tests and questionnaires of real or potential users.

Toplighting systems in sports halls

Despite the fact that the challenges described are numerous, the architectonic space of sports halls offers a suitable opportunity for daylighting integration. In this sense, in particular top-lighting has a great potential to adequately day lit the court or the field of play, because buildings have typically deep plan layouts and large span roofs, see examples in Figure 1-18, Figure 1-20Figure 1-21Figure 1-22. Moreover, sidelighting such as windows are low performing and typically unable to bring daylight into deeper spaces, including being more likely a source of glare.

Daylight optimization in sports halls in Catalonia

Finally, the current technical regulation or Master Plan for sports facilities and infrastructure in Catalonia-PIEC (Generalitat de Catalunya 2005a) establishes the mandatory requirement to provide daylight in indoor sports halls, among others, see *Figure* 1-19**.** It also gives a series of recommendations to guarantee the balance between the use of natural light and the achievement of other objectives, such as sustainability and energy saving in general, both in new and existing buildings. As a consequence, the daylight optimization has to be considered from the earliest stages of design, both in new and retrofitting design projects of sport facilities.

Figure 1-13. Images of sports halls with toplighting and sidelighting systems in Barcelona.

Pavelló Municipal Virrei Amat - PMVA (20/09/2006 1:30 pm, clear sky), left. Centre Esportiu Municipal La Verneda - CEM LV (1st/02/2007 12:30 pm, clear sky), right.

Figure 1-14. Images of the celebration of the Barcelona 1992 Olympic Games.

Opening ceremony: Antonio Rebollo, ESP (Source: © 1992/ Allsport/ Bruty, Simon[1]), left. Diving 10 m platform: Veronica G. Ribot de Canales, ARG (Source: ©1992/ Allsport/ Duffy, Tony[2]), centre. Basketball final: Croatia vs. USA, (Source: ©1992/ Allsport/ Powell[3]), right.

Figure 1-15. Images of athletes in Olympic sports competitions.

During the sports activities, there are diverse dynamic physical movements and visual tasks: the 2004 OG Athens, GRC, Basketball semi-final competition: ARG vs. USA (Source: ©Chris McGrath/ Getty Images[4]), left. The 2016 OG Rio de Janeiro, BRZ: Foil Individual Men's fencing in: Russia vs. USA (Source: Getty Images[5]), right.

1 https://blog-tom.com/slider/slide/favourite-jason-evans.html#slide=2

2 https://blog-tom.com/slider/slide/favourite-jason-evans.html#slide=3

3 https://blog-tom.com/slider/slide/favourite-jason-evans.html#slide=9

4 https://www.olympic.org/athens-2004/basketball

5 https://www.olympic.org/news/history-repeats-itself-in-rio-for-yog-fencer-massialas

1.5 Hypothesis of the research

From an architectonic design approach, the hypothesis of this research work is if the use of daylight in sports halls in Mediterranean climates by toplighting could contribute to the user's visual comfort by suitable design strategies. In other words, if toplighting systems can perform adequately in terms of quality and quantity of natural light, from a comprehensive assessment of visual comfort in this specific type of buildings: the sports halls, see Figure 1-12 and Figure 1-13.

The aim of the research work is to highlight the functional use of toplighting in sports halls, while considering the impact of the architectural design strategies: daylighting systems and the luminous environment, see

Figure 1-16:

How daylighting, and toplighting in particular, could contribute to the visual comfort of users in sports halls in Mediterranean climates?

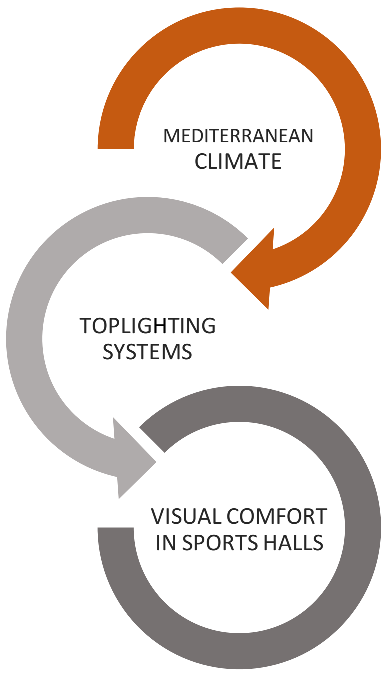

Figure 1-16. Graphic with the main topics covered by this thesis work.

Moreover, derived research questions could be extracted from the main hypothesis as follows:

- If toplighting perform better than sidelighting, in this specific type of building: the sports halls
- Which are the most effective daylighting design strategies and measures to improve the visual comfort in sports halls?
- Which are the preferences for users in daylit sports halls, regarding their visual comfort in training and competition levels of play?

Figure 1-17. Images of the court of the Complex Esportiú Consell Català de l'Esport- CECCE building in Barcelona.

CECCE (13/2/2007 12:45 pm, clear sky) in training conditions: athletes are moving into the space during the volleyball match and performing a dynamic visual task.

Figure 1-18. Images of top-lit Olympic sports halls.

The interior architectural elements and the daylighting systems define the visual environment: the Badalona Sport Palace- Palau d'Esports de Badalona, Badalona, ESP (Source: ©Gina Barcelona[6]), left. The Water Cube, the Olympic swimming pool in Beijing, CHN (Source: ©Martin Eckert[7]), right.

Figure 1-19. Images of sports halls with toplighting and sidelighting systems in Barcelona.

CEM La Verneda CEM LV (12:30 1st/02/2007, clear sky) with central skylight, left. INEFC M (17/02/2008 12:45 pm, overcast sky) with pyramidal skylights, centre. CEM Can Ricard CEM RCR (30/09/2006 10:45 am, intermediate sky) with lineal skylights and side windows, right.

6 http://www.ginabarcelona.com/proyectos/olympic-pavilion-in-badalona/
7 https://www.flickr.com/photos/meckert75/3732780382/in/photostream/

The hypothesis is also related to the fact that the implementation of toplighting in sports halls in middle latitudes could contribute to architecture and sustainability, according to the following:

- To improve the environmental quality of the indoor space and users' well-being by providing natural lighting
- To achieve user's visual comfort during the daytime, considering visual comfort requirements of different users, see *Figure 1-17*. Additionally, it could contribute to energy savings by reducing artificial lighting and avoiding harmful effects on the environment

1.6 Objectives and expected results

The main goal of this work is to highlight the important role of the architectonic design of the luminous environment and to encourage the implementation of daylight in sports halls, taking into consideration the user's visual comfort. For this purpose, an objective assessment of the daylight systems and their performance is required, in terms of light quantity and quality. As well, to study their contribution to visual comfort of sports hall users.

The expected results and secondary objectives of this research work are outlined below:

- To design a methodology to perform an objective and subjective evaluation of users' visual comfort in this specific type of building, and particularly, in the court or field of play
- To identify different visual requirements for the users of sports halls: athletes, spectators or public, and TV broadcasting or remote public
- To elaborate an inventory of frequent situations regarding the users' visual comfort or discomfort in sports halls spaces under daylight
- To incorporate, test and validate measures for the visual comfort improvements, based on design strategies
- To explore and assess the preferences and dislikes of users, as athletes and spectators, in different simulated luminous environments or scenarios
- To elaborate design guidelines and recommendations to implement daylighting strategies and natural light optimization in sports halls, regarding the users' visual comfort and the natural light characteristics in Mediterranean climates

1.7 Research methodology

The proposed methodology combines different techniques to obtain results of daylighting systems performance and visual comfort, from a holistic approach. Likewise, the methodology includes a functional and architectural point of view to integrate users' visual comfort requirements and the luminous space/environment from qualitative and quantitative assessments.

Figure 1-20. Images of Secondary School and Hall in Klaus (AT) with toplighting systems.

Secondary School and Hall (Dietrich | Untertrifaller Architekten, 2013-2014, 2002-2003) with 56no. pyramidal skylights and luminaries integrated into the ceiling soffit (Source: ©Bruno Klomfar)[8].

Figure 1-21. Images of sports halls with toplighting and sidelighting systems.

Municipal Sport Halls in Olot, (ES) (BCQ Arquitectura Barcelona, 2006-2010): monitor roof and multilateral windows, (Source: ©Pedro Pegenaute[9]) left. Gymnasium Alice Milliat in Lyon (FR), (Dietrich | Untertrifaller & Têkhnê Architectes, 2014-2016): pyramidal skylights and unilateral side windows and clerestory, (Source: ©Julien Lanoo[10]) right.

Figure 1-22. Images of the Catalunya Sports Palace – PEG in Tarragona (ES), with toplighting and sidelighting systems.

Palu d'Esports Catalunya -PEG (Balanzó Arquitectes SLP & AIA - Activitats Arquitectòniques, 2016-2018) with a central skylight and multilateral side windows, (Source: ©Simon García[11]).

8 https://www.dietrich.untertrifaller.com/en/projects/hauptschule-und-mehrzweckhalle-klaus-at/?filter=373&parent=369

9 http://bcq.es/portfolio/municipal-sports-hall/

10 https://www.dietrich.untertrifaller.com/en/projects/sporthalle-alice-milliat-lyon-fr/?filter=543

11 http://www.bbarquitectes.com/es/work/equipamiento-deportivo-juegos-del-mediterraneo-tarragona-2017/

Functional approach

The functional use of toplighting in architecture refers to the use of natural light resource for visual activities. That it is not more or less important than other purposes of integrating natural light in architecture, as a decorative, playful or symbolic feature (Serra and Coch 1995).

To perform a functional assessment of daylighting systems in sports halls, a combination of quantitative and qualitative evaluation was used in the methodology. The objective data, that will be provided in terms of the fulfilment of visual comfort requirements, including the following procedures:

- Experimental measurements by vertical and horizontal illuminance survey in the court/field of play and seating area
- Definition of multi-spatial view directions and users´ field of view – FOV by HDRI assessment
- Luminance spot measurements in relevant points and regions of the users' field of view – FOV
- Static simulations and scale models are used for the calibration of baseline models and to the enhancement of the in-situ data acquisition
- Photorealistic renders by static numerical simulations are used for performing a psycho-visual test, to compare existing and improved visual comfort measures conditions by potential users

The subjective data are related to the preliminary assessment of the daylit sports halls by the author and users' preferences and rejection criteria of participants. These preferences and rejection criteria were collected during an experimental test, to choose the more comfortable light environments.

The architectural point of view

The comprehensive point of view of the subject is defined by my profession and experience in the field of design and architecture, including multiple methods and procedures proposed.

Moreover, the physical luminous space or the built environment is featured by architectural surfaces as a result of design strategies, defining the visual perception and the experience of users.

In this specific type of building, the luminous environment is evaluated taking into account how the daylighting systems and the interior architectural design impact the visual comfort from the perception of the sport hall users: athletes, spectators and broadcasting television - remote viewers.

1.8 Thesis structure

The thesis has been organized into six main parts, see Figure 1-23, according to the following:

- The Introduction, the State of the Art and the Research Methodology, Chapters 1, 2 and 3
- 1st Part: Visual comfort in sports halls of the Barcelona 1992 Olympic Games, Chapters 4 and 5
- 2nd Part: Assessment of daylighting design strategies to improve visual comfort in sports halls using simulations and experimental test, Chapters 6 and 7
- 3rd Part: Daylight optimization in a new sports hall of the Tarragona 2018 Mediterranean Games, Chapter 8
- The Conclusions, future work and daylighting design recommendations, Chapter 9, including the Appendix I
- The Appendices: I, II, III and IV

This current Chapter 1 is an overview of the research work, summarizing the main issues covered by this study and the key factors to understand the methodology proposed to demonstrate the research hypothesis in terms of: daylighting systems, sports hall buildings and visual comfort.

Chapter 2 summarizes the state-of-art and the framework where this research and the methodology is based on. For that, an extensive bibliographic review was developed and presented in 3 main subjects as follows:

- Natural light - daylight
- The luminous environment: sports halls architecture
- Visual comfort

Chapter 3 describes the methodology approach from a comprehensive point of view and the different phases and the procedures implemented to conduct this research. A combination of quantitative and qualitative methods was also used in the data analysis from existing sports halls in Barcelona.

The first part of the development of the methodology is composed of 2no. chapters. It contains the case studies description and the preliminary and detailed assessments, including the discussion of results.

The case studies are presented in Chapter 4, comprising the reference sample of 13no. sports hall buildings, which was chosen to perform a preliminary evaluation. Finally, four of these top-lit case studies were selected as final sample, built for the 1992 Olympic Games in Barcelona. The final sample is selected to perform a comprehensive and detailed assessment of users' visual comfort.

Chapter 5 summarises the preliminary results, after the assessment of existing conditions in the reference sample. It includes a diagnosis where the most critical situations found and linked to the visual discomfort are highlighted, focusing on the users as: athletes, spectators, and television broadcasts. Based on this diagnosis, a catalogue of frequent situations is also discussed.

The second part is divided in two chapters, covering the design strategies and measures to improve the user visual comfort, the experimental test and subjective assessment by participants.

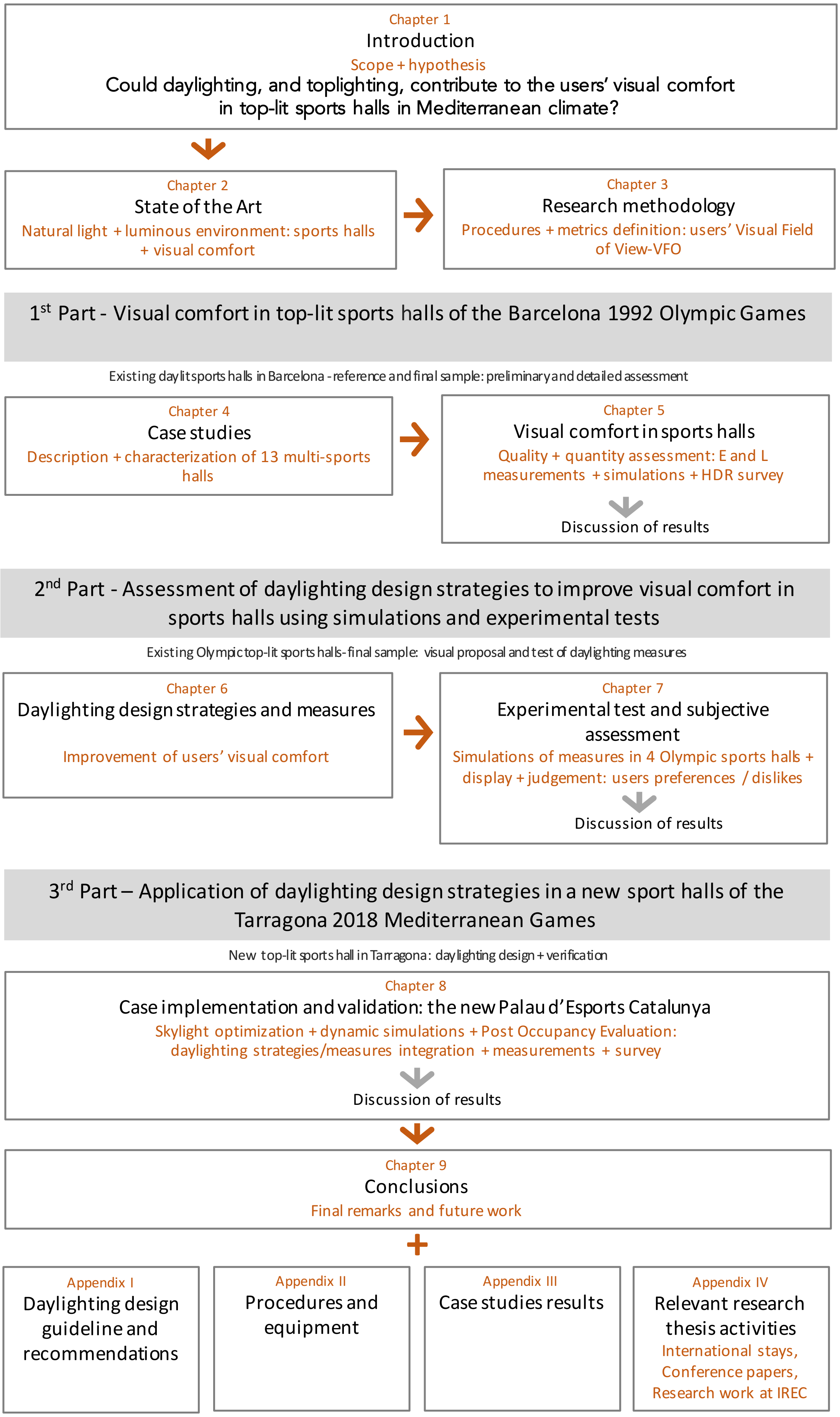

Figure 1-23. Thesis structure scheme

Chapter 7 reviews the psycho-visual test that was performed and tested with 32no. subjects. The test included different daylight scenes or environments where the selected measures have been applied. A comparison about the real performance or current operation against the visual comfort improvements was carried out for training/athlete point of view and competition conditions/spectators point of view.

Furthermore, this chapter summarizes the main findings of the test realization including the qualitative assessment of subjects' responses for both users: athletes and spectators, linked to the objective results of the visual environment under daylight conditions.

Additionally, the test results provide qualitative information about which aspects are considered significant by users, in terms of achieving a comfortable luminous environment, so the most relevant preferences and dislikes for sports hall users are also discussed.

The third part is covered by Chapter 8 which presents a review of the skylight optimization by dynamic simulation in a new sports hall in Tarragona: the Palau d'Esports Catalunya, built for the 2018 Mediterranean Games.

Moreover, the theoretical simulation results are contrasted with the outcomes of the visual comfort assessment with Post-Occupancy Evaluation – POE during the building use. The POE assessment includes the results of around 140no. spectator surveys that were obtained during the realization of the Tarragona 2018 Mediterranean Games.

Finally, Chapter 9 summarizes the study´s key findings, conclusions and defines future research work. It also contains the contributions of this work such as the suitable performance of top-lit sports halls in Mediterranean climates, providing good levels of illuminance, uniformity and reducing glare situations on the court. This is also in accordance with subjective preferences by users. In addition, it emphasizes the complexity of the architectural design of the luminous environment with daylight and moving users in sports halls. The importance of integrating daylighting strategies in the early stages of the design project is also highlighted.

Daylighting design guidelines are presented as a final outcome, with the support and commissioned by the Consell Català de l'Esport - CCE of the Catalan Government. These recommendations aim to encourage the implementation and optimization of natural light in sports halls in Mediterranean climates from early design phases, which are presented in Appendix I.

Following the last chapter, four appendices are included containing:

- Appendix I: Daylighting design guidelines and recommendations
- Appendix II: Procedures and equipment
- Appendix III: Case studies results
- Appendix IV: Relevant research thesis activities, including the two international stays, supported by the Catalan Agency AGAUR, which were carried out at the University of Lyon and the University of Buenos Aires. It also presents published papers and research work at Catalonia Institute for Energy Research – IREC

2

State of the Art

This chapter discusses the framework where this research and methodology are based on. A bibliographic review was developed within this thesis work in three main subjects: natural light and lighting, the luminous environment, such as sport hall buildings, and the visual comfort. Monitoring and simulation techniques are also included for the assessment and prediction of quality and quantity of daylight in buildings, such as horizontal and vertical illuminance, luminance maps for distribution and contrast in the visual field, glare sources and virtual models, among others. These topics are relevant and useful to understand the procedures and techniques chosen to carry out this research.

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Natural light, architecture and visual perception

The visual comfort is a subjective perception by users and it is related, in general, with their interaction with the physical environment and light.

Accordingly, in this study, this research is focused on the natural light interaction with the architectonic space, and the impact affecting the users' visual perception when they are performing a specific visual task, see Figure 2-1. Three main topics will be developed and linked in this chapter: the daylight, see section 2.1, the users visual comfort in sports halls: athletes, spectators and remote audience, including broadcasting requirements, see section 2.2 and the sports halls with specific architectonic features, see section 2.3.

2.1 Natural light - daylight

In this work, the term daylight will be used as a synonym of natural light, including all the providing sources as direct light from the sun, diffuse light from the sky dome and reflected from the outdoor/indoor environment.

The most powerful source of light is the sun. As human beings, we are strictly dependent upon the everyday sun radiation like the majority of living species (Fontoynont et al. 2004).

One of the major characteristics of natural light is its variability in terms of intensity, direction and colour temperature. All of these fluctuate during the day, seasons and the year, defining the daylight dynamics, see Figure 2-2. Furthermore, daylight is totally free and its availability depends on many factors, but abundant in the whole planet.

Daylight also is strongly correlated with climate and latitude characteristics that both define: the sun availability during the day and year, the atmospheric conditions, outdoor environment, and the proportion and frequencies of clear, intermediate and overcast sky distribution during the year.

Although the light wasn't certainly studied from comprehensive and holistic approaches, it has been largely studied by different disciplines (López-Besora 2015). For example, it was studied in medicine, in particular their psychological and physiological effects in humans.

Light was characterized by physics as energy, the light interaction with the matter or the physical environment, as electromagnetic wave which propagates by radiation. The visible range of the electromagnetic field for humans is between 380 and 780nm wavelength (Boyce 2014), see Figure 2-3.

The most common characteristics to define light are the following parameters (Ruck et al. 2000; Jacobs 2003 and 2004):

- Luminous Intensity-I [candela-cd]: describes the power of light source, to emit light in a given direction
- Luminous Flux-F [lumen-lm]: is the measure of the power of visible light, according to the response curve of the human eye

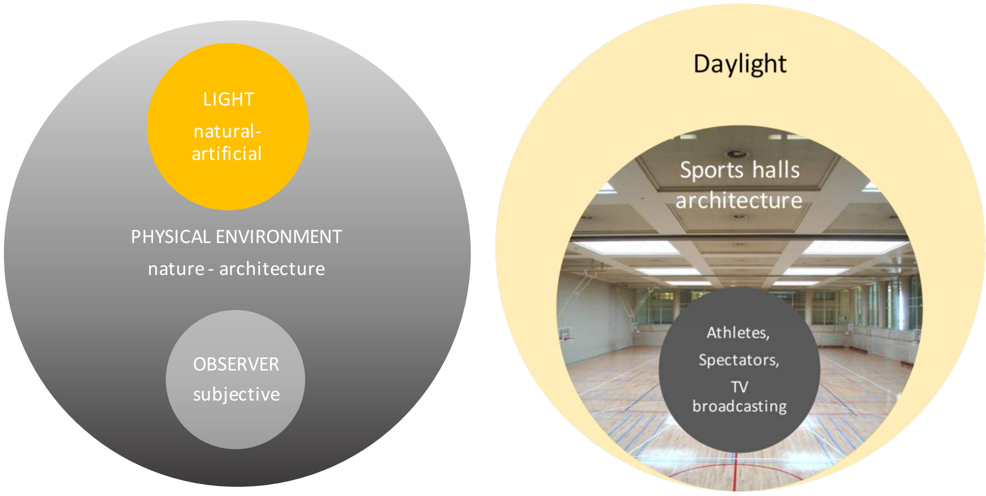

Figure 2-1. Schemes of the principal factors defining visual comfort in general.

Visual comfort depends on light, physical environment and observer, left, and in this particular study: daylight, sports halls architecture and athletes, spectators - TV broadcasting, right

Figure 2-2. Image with the dynamics of daylight in 24h: position of sun or light direction and colour spectrum[1].

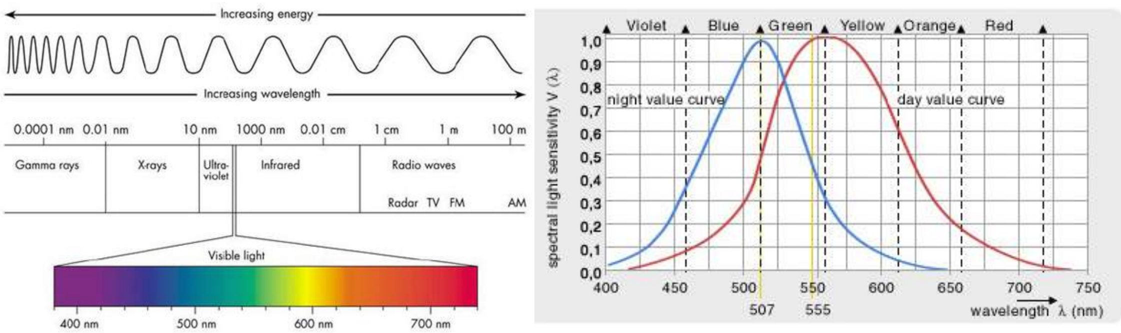

Figure 2-3. Graphics showing the visible range[2], left, and the spectral light sensibility and wavelength, right[3].

[1] Source: https://www.zumtobel.com/PDB/teaser/EN/Active_Light_general.pdf

[2] Source: http://edisontechcenter.org/lighting/index.html

[3] Source:http://www.osram.com.sg/osram_sg/Lighting_Design/About_Light/Light_%26_Space/Technical_basics_of_light__/index.html

- Directionality: is the balance between the diffuse and directional components within the luminous environment (Inanici 2006). Direct sunlight and specular reflections are typically directional light. Per contrary, the greater the amount of diffuse light, the less shadowing occurs, reducing the user's ability to evaluate depth, shape, and texture of a surface. Directionality of light is required to model and evaluate three dimensional objects. The good balance between diffuse and directional light enables the user to evaluate the smoothness, grain, specularity, and other properties of a surface (Ruck et al. 2000, pp. 3-7)
- Colour temperature [kelvin-K]: describes the colour of light sources, indicating the equivalent temperature that a black body radiator would need to have in order to reproduce light of the same colour (sun 5800k, overcast sky 6000k, candlelight 1850k)
- Time: especially important in the case of natural light, because time of the day and month define altitude and azimuth of the sun and colour temperature

Therefore, this work refers to the characteristics of natural light and their effects and interactions affecting humans in terms of: the non-visual and visual photo-reception, including the visual task performance and with architectural spaces or built environment.

Dynamic effects of natural light

Daylight has significant functions in humans, as in all the rest of living organisms, in different levels. The most important functions studied are the following:

- Visual photo-reception, to allow the assimilation of visual information through the visual system, including the sense of time, orientation, and a specific visual task
- Non-visual photo-reception, to allow physio or biological and psychological or emotional processes and responses, e.g. Alertness, mood, production of hormones, circadian and biological clock

Nowadays, the contribution of dynamic natural light to indoor spaces, in terms of intensity of light and light wavelength or colour spectrum, has been emphasized due to its benefits to guarantee the health and well-being of building occupants (Giarma, Tsikaloudaki and Aravantinos 2017). One important reason for this is that the production of many hormones and enzymes are related to the cycles of daylight-day and darkness-night.

This thesis is based on the study of the visual effects of natural light related to users' visual comfort and its interaction with the built environment (architecture). However, the non-visual benefits of natural light in humans, the physiological and psychological or circadian effects, are not explored in this research but they must be considered as one of the major features to optimize the use of daylight in buildings.

2.1.1 Light and daylight metrics

The most extensive bibliography and regulations in the last century are developed for lighting in buildings with artificial light. However, the standards metrics and minimum levels for daylighting have not yet agreed, with the exception of the Daylight Factor DF%, established by Moon and Spencer in 1942 (cited in Rockcastle and Andersen 2013).

Figure 2-4. Images of different buildings with toplighting strategies in non-residential buildings.

Examples of top-lit buildings in Barcelona: central skylight and multilateral clerestory in the Terminal 1, Airport of Barcelona, Prat de Llobregat, left. Linear skylight in Maldà commercial galleries, Gòtic, centre. Linear single monitor roof after rehabilitation works in Vapor Vell library, Sants, right.

Figure 2-5. Images of buildings with toplighting strategies in residential and non-residential buildings.

Examples of top-lit buildings in France: bilateral clerestory in Le Corbusier Foundation (2007), Paris, left. Glazed roof and atria at the Helios building of LEPMI Laboratory (2013), Le Bourget-du-Lac, right.

Figure 2-6. Images of the Galleries Lafayette building with a central skylight.

Glass and steel dome central skylight in Galleries Lafayette (2010), Paris, Haussmann (Cheddane, G. and Chanut, F. architects, 1912): exterior view, left. Interior from the ground level, centre, and partial view from the side, right.

The toplighting systems can distribute daylight into deep plans. Skylights and atria are examples of that, providing natural light on the ground floor and the adjacent spaces. However, the solar protection can be an issue in top-lit spaces, most of all, in latitudes and climates with high solar radiation on the horizontal plane.

The CIE - Commission Internationale de l'Éclairage established that good lighting requires equal attention to the quantity and quality of the light. So, lighting quality is more than just providing a suitable quantity of light. In other words, the quality of light depends on many factors and related to their effects on people.

According to that, the light metrics that count for daylighting will be presented as follows, in two main categories: quantitative and qualitative metrics.

The quantitative metrics are the following:

- Illuminance - E (Lux), including horizontal illuminance - E_h and vertical illuminance - E_v

The contributors to lighting quality (Veitch & Newsham 1998) are the following, that will be also presented as qualitative and visual comfort metrics, see also section 2.2.6 below:

- Illuminance uniformity
- Luminance - L (cd/m^2)
- Luminance ratio or contrast
- Light colour characteristics or Colour Index Rendition (%)
- Glare

More recent approaches emphasize that the lighting quality depends on a number of factors, including physical and psychological parameters (LEARN London Metroplitan University 2004). In this sense, it is also linked to the user' interactions with the ambiance, the performance of the visual task and the visual comfort. So, it is not inherent of a space or a lighting design.

Illuminance- E

The illuminance E, in lux unit, provides the amount of light that reaches a given surface (horizontal or vertical). This information allows to verify the amount of incident light in a given plane, an object or a certain surface.

This metric is useful to have quantitative data of incident light in the horizontal and vertical planes.

Horizontal Illuminance- E_h

The horizontal illuminance -E_h measurement is one of the most well know technique for assessing lighting hitting a surface. The horizontal illuminance provides the amount of light that reaches a horizontal surface or commonly, a work plane.

Moreover, all of the existing regulations use this parameter, horizontal illuminance - E_h, to establish the minimum values required to perform a specific visual task, according to the type of building. However, it does not reflect other important information, regarding the requirements for the visual task performance, for example: direct and indirect reflexes, glare, adaptation, excess of contrast, see section 2.2.2 below.

This is a significant metric, since for each visual task, a minimum amount of light incident to the so-called work plane is required. Likewise, they are defined as a quantitative parameter in terms of visual comfort, although others parameters could be also required to perform a specific visual task.

Vertical Illuminance- E_h

The vertical illuminance - E_v 90° is used to know the amount of incident light in a vertical surface, or hitting the user's eye or on a device, such as video and/or photographic cameras.

In sports halls, the orientation of vertical planes to determine E_v is the same for all sports areas and parallel for the four side lines, resulting in four vertical plane values, recommended to be measured at the horizontal grid (CIE 67:1986). Also, one reading has to be taken at each grid point on a normal plane to the camera position, rotated in azimuth to face the camera.

The illuminance E and horizontal illuminance E_h described are most commonly evaluated in a horizontal plane, which leaves a gap with respect to the visual field with a vision in 360°, where the so-called work plane is vertical, not horizontal. For this reason, the E_v is useful for dynamic visual environments and television broadcasting. Some lighting regulations contain minimum values of E_v vertical illuminance, such as those related to this work, in particular, as guide for the lighting of sports events for colour television and film systems (CIE 83:1989; UNE-EN 12193:2020).

Illuminance uniformity

The illuminance uniformity is the ratio between the measured values of minimum illuminance E_{min} and the average E_{av} or the maximum illuminance E_{max} on the work plane or vertical plane, see Equation 2-1.

$$U_1 = \frac{E_{min}}{E_{av}} \qquad U_2 = \frac{E_{min}}{E_{max}}$$

Equation 2-1. U illuminance uniformity formulas: U_1 and U_2, according to UNE-EN 67:1986 and UNE-EN 12193:2020.

Where:

E_{min}= minim illuminance measured at a point on the work plane, E_{av}= average illuminance measured at a point on the work plane, E_{max}= maximum illuminance value measured at a point on the work plane.

This parameter gives information about how the illuminance is distributed in a surface or work plane, from minimum values = 0 and the maximum=1. In the case of sports halls, minimum thresholds of illuminance uniformity are set according to the level of play (training or competitions).

The lighting standards frequently contain recommendations and methods to measure, regarding the uniformity of illuminance in the working plane, for example for lighting in sports halls (UNE-EN 12193:2020), see section 2.3.3.

According to UNE-EN-12464-1:2011 the illumination of the task area and its immediate surroundings should provide a well-balanced luminance distribution in the field of view, instead of luminance ratios (Dubois et al. 2016a).

Luminance

The luminance values (cd/m^2) reflect the amount of light that falls on a point, observer' eye or object, from a certain point and direction. These values *per se* are not indicative of comfort or discomfort conditions, but they are relative of other points of the visual field, see section 2.2.

Luminance ratio or contrast

To measure the spatial distribution of light, luminance ratios on task and certain architectural elements, such as walls, ceiling and surroundings can be extracted to reflect the luminance variability across a plane or surface. Maximum, minimum and average values can be extracted in the whole scene, on a surface or a region of interest (Inanici 2005b).

The luminance contrast can be established as the difference between the L_t luminance of the target and L_b background, see equation below:

$$C = \frac{(L_t - L_b)}{L_b}$$

Equation 2-2. Contrast formula (Source: Inanici 2005b, pp. 23)

Where: L_t =luminance of the target, L_b = luminance of the background

Colour index rendition

The natural daylight defines the full spectrum of lighting or true colour rendition (Ruck et al. 2000, pp. 3-9). The colour rendering is a useful parameter, most of all in tasks that involve quality control, colour matching and accurate colour perception.

The spectral distribution of light source after it enters the building determines colour rendering. Commonly, daylighting systems, are the less that changes colours due to the natural light offers full spectrum lighting. However, complex daylight systems and glazing characteristics may change the transmitted light spectrum and reduce the colour perception, for example: tinted, coloured, holographic and diffractive glazing.

Finally, the perception of colours and overall luminous space could be affected by the daylight components of direct, diffuse and reflected light.

Colour temperature

The colour temperature of light is a useful factor, most of all in artificial lighting. However, it has to be considered also under daylight conditions, because the glazing materials could affect the colour of transmitting light. The user visual comfort zone in the graphic of Kruitoff is related to the quantity and the quality of light: level of E illuminance (Lux) and temperature of light (°K), see Figure 2-7.

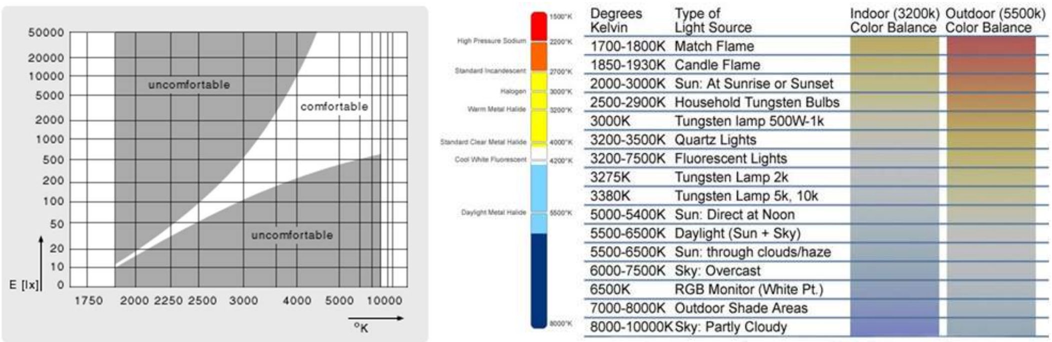

Figure 2-7. Graphic of Kruitoff[4], left, concerning the illuminance level and temperature of light, and graph of temperature of light and colour balance[5], right.

Glare

The Commission Internationale de l'Eclairage- CIE (CIE 17.4-1987, cited in CIE 112-1994), refers to glare as "condition of vision" which includes two separate psycho-physical effects, and these forms are quite different phenomena: disability glare and discomfort glare, see section 2.2.3.

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[4]Source:http://www.osram.com.sg/osram_sg/Lighting_Design/About_Light/Getting_the_best_possible_light__/The_perfect_light_design/index.html

[5] Source: http://www.3drender.com/glossary/colortemp.jpg

Another definition of glare (IESNA 2000) is "the sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort or loss in visual performance and visibility".

Daylight metrics

At present, the most used daylight metrics can be divided into two main categories (Rockcastle and Andersen 2013): the illumination for task-performance and the visual comfort metrics, see section 2.2.4 below.

A less established category can be mentioned in third place (Rockcastle and Andersen 2013) as the perceptual daylight metrics such as the average luminance, luminance range and deviation, and spatial or compositional luminance within the occupants' field of view – FOV. This is increasingly important in daylight design and user's preferences, see sections 2.2.5 below.

Illumination for task-performance

The illumination for task performance is used to determine if there is sufficiently illuminated work plane for the performance of a specific visual task. It includes the static Daylight Factor DF% (Moon and Spencer 1942, cited in Rockcastle and Andersen 2013), the dynamic annual based Daylight Autonomy - DA% (Reinhart and Mardaljevic 2006) and the Useful Dynamic Illuminance- UDI% (Mardaljevic and Nabil 2006) described below.

Daylight Factor

The daylight factor - DF is the most common and extended daylight metric, expressed as a percentage. It is a specific factor describing the ratio of the internal illuminance at a point in a building, on the horizontal work plane, compared with the unshaded external horizontal illuminance, under a CIE overcast sky (Moon and Spencer 1942, cited in Reinhart et al. 2006).

The higher DF, the more daylight is available in the room. Note that this factor must be obtained under fully overcast sky conditions and simultaneously with unobstructed exterior E_h measurements, see xxx.

$$DF = \left(\frac{E_{in}}{E_{ext}}\right) * 100\%$$

Equation 2-3. Daylight Factor DF % formula.

Where:

E_{in} = interior horizontal illuminance measured at a point on the work plane.

E_{ext} = simultaneous exterior horizontal illuminance from unobstructed overcast sky.

According to most standards, an average of DF at least 2% at working places should ensure minimum daylight levels (Dubois et al. 2016). DF values up to 5% are desirable in indoor spaces (CIBSE 2002), but with values higher than 3%, glare should be verified.

In most cases, DF levels are measured in a room at work plane height, according with the visual task or activity, for example at 0,85m.

One of the major advantages of DF is that it allows to compare the values obtained in different conditions: buildings, latitudes, days of the year and time, since it is not an absolute value but relative. It can also be plotted on a floor plan or map showing calculated values and points, for example, as a plan of the studying space with reference and significant points.

However, the DF has limitations such as it does not take into account the climate conditions, including fluctuations in the intensity of daylight due to sky conditions and orientation. The DF cannot be used as design criterion under clear sky conditions, since it varies significantly throughout the day (Fontoynont et al. 2004).

Daylight Autonomy

The Daylight Autonomy- DA is an annual based metric and commonly referred as a dynamic daylight metric, which can be calculated by daylight dynamic simulations by RADIANCE software (Larson and Shakespeare 1998). It can be also obtained by other softwares based on RADIANCE, as DAYSIM (NRC ISE 2012; Reinhart and Walkenhorst 2001; Reinhart 2006) and DIVA-for-Rhino (Solemma 2011). DA is represented as a percentage of the occupied time when the illuminance target, commonly as horizontal working plane, at a given point, is met by daylight (Reinhart 2004; Reinhart and Mardaljevic 2006). It combines the geographic information, as latitude and weather data in annual basis, and also the potential energy savings in artificial light if the lighting criteria is defined in the simulation, for example the electric power installed and work-time schedules (Reinhart 2004).

For example, to obtain 3 possible points for Daylight in new buildings in the LEED rating system (U.S. Green Building Council 2020), a threshold of spatial daylight autonomy – $sDA_{300/50\%}$ has to be simulated and demonstrated, meaning that 50% of the time daylighting levels are above the target illuminance of 300 lx at least in the 40% up to the 75% of the regularly occupied floor area.

These values are promoted by the Illuminating Engineering Society of North America- IES (cited in U.S. Green Building Council 2020).

Useful Daylight Illuminance

The Useful Daylight Illuminance- UDI is a dynamic daylight performance measure and it is also based on the DA, illuminances on the work plane, and the Climate-Based Daylight Modelling- CBDM. It was proposed by Mardaljevic and Nabil (2005), using realistic skies and sun conditions (Reinhart et al., 2006).

It aims to determine when daylight levels are useful for the occupants, for example: too dark <100 lx, and too bright >2.000 lx. This range is founded on reported users' preferences in daylit offices (Mardaljevic and Nabil 2005). Based on these thresholds, the UDI results in three metrics: UDI < 100 lx, fell short, UDI 100 – 2.000 lx the level is achieved, and when it was exceeded UDI >2.000 lx and is meant to detect the likely appearance of glare and/or thermal discomfort.

Visual comfort metrics

The visual comfort metrics comprise the prediction or the analysis of the existing discomfort glare probability under daylighting conditions in offices spaces: the Daylight Glare Probability - DGP (Wienold and Christoffersen 2006) and the simplified DGPs (Wienold 2009) which has also developed into a dynamic annual based simulation (Jakubiec and Reinhart 2012), see section 2.2.

2.1.2 Daylighting in buildings

In this work, the term daylighting, specifically, refers to the technique to bring natural light to architectural spaces through the openings (Fontoynont et al. 2004) and, in particular, means to day-lit indoor spaces.

The position and size of openings, the shape and interior features of the built environment, determines the access and distribution of daylight indoors (Fontoynont 1999).

Daylight sources

Light can be classified into directional or diffuse components, which defines the architectonical features, in terms of how the sources of natural light are used.

The directional component includes:

- The direct light from sources
- Specular reflections

The diffuse reflections refer to the Lambertian components from all surfaces other than light sources (Inanici 2006, pp. 100-101) as follows:

- The skylight,
- Reflections of solar radiation from outside surfaces,
- The diffuse reflections of skylight from outside surfaces and
- Diffuse interreflection within the interior space

2.1.3 Daylighting design strategies and systems

Daylighting strategies refers to the different design and technical specifications for fenestrations placed in buildings (Moore 1985), with the aim to bring natural light to indoors. Daylight strategies and daylight systems have the purpose of collecting natural light and deliver it into indoor spaces, and are usually comprised of the following elements:

- Openings: shape, size and position related to the building
- Glazing surfaces: glass, plastic, transparent or translucent materials
- Solar protection, control and regulation of light: sunshade, sun and light screen filters and blackout devices

The openings, their size, position and materialization play an important role, modifying the quantity and quality of light that penetrates in the space. In other words, they determine the use, optimization and/or protection from the natural light sources:

- Direct light or sunlight: the light from the sun beams
- Diffuse light or skylight: the light provided from the sky dome
- External reflections: direct and diffuse light reflected from exterior elements, such as the ground, building and vegetation, among others
- Internal reflections: light reflected from indoor surfaces

The two major fenestration strategies are:

- Toplighting, daylighting from above, placed in the top of buildings, ceiling and roof plane, with horizontal or tilted openings
- Sidelighting: daylighting from the façades, most of all vertical or tilted openings, respectively.

Furthermore, related to the location and direction of the daylighting systems into the building, these strategies can be also a combination of both.

Advanced daylight systems can also include selective reflectors, tunnels and transport light systems, active and selective surfaces and sun path tracking systems, e.g: sun pipes, light tubes, mirrored light shelves.

Toplighting

The major characteristic of toplighting systems is that it can contribute to daylight the deep interior spaces or plans, because it can be uniformly distributed along the space from the top. However, they can be used only in the last level, over the roof. The most common systems implemented in buildings are rooflights, skylight and clerestory, see Figure 2-8. Clerestories can be defined as well as high windows, when placed above of the line of vision.

Skylights, in particular, are basically designed to allow the sky dome light with diffuse light, but the design has to be especially careful with the direct light or sunlight. It can be designed either for clear or cloudy skies, however the most significant characteristics of this strategy is in what way skylights deal with direct sunlight (Ruck et al. 2000). The most common designs for skylight are: flat, shed or pitched roof, barrel and half barrel, pyramidal and dome.

The northlight and the sawtooth have similar characteristic when glazing apertures are oriented to North. However, in the case of the sawtooth the vertical apertures can be easily shaded from direct sun by overhangs.

Monitor configurations have vertical glazing apertures in two orientations, and North-South orientation is preferable for solar control.

All types, except flat and dome rooflights, are sensitive to orientations, taking in account the solar control requirements to avoid direct solar radiation (Fanchiotti and Amorin 2000). Special considerations have to be made in other orientations different from North, to take into account solar penetration (Baker, Fanchiotti and Steemers 1993; Baker and Steemers 2002).

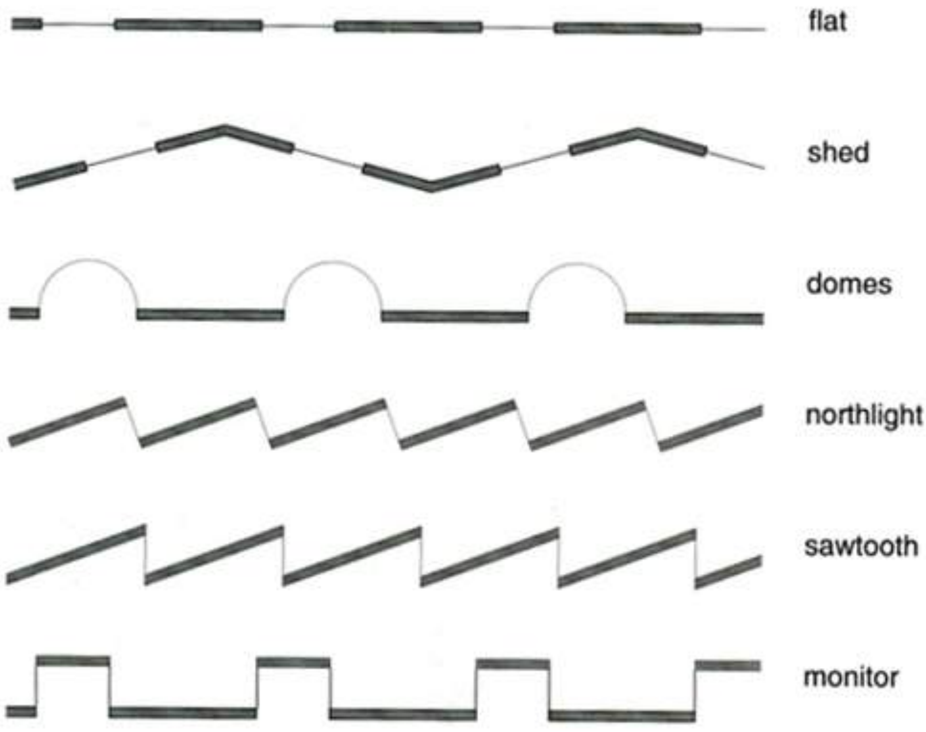

Figure 2-8. Scheme of toplighting systems: rooflights configurations according to the CIBSE nomenclature (Source: Baker and Steemers 2002, pp.70).

Figure 2-9. Images showing windows in residential and non-residential buildings.

Building examples in Barcelona: exterior of Casa Batlló in St Jordi (2016) (Sala Cortés, E., 1877, Gaudí, A., 1906), left. Auditorium gallery of Universitat de Barcelona (2010) (Rogent, E., 1889), centre. Double skin façade in CosmoCaixa (Doménec Estapá, J., 1909, Garcés, J. and Soria, E. 1980, Terrades, R. and Terrades, E., 2004), right.

Figure 2-10. Images showing unilateral and multilateral windows in residential building in France.

Maison La Roche, actually as museum Le Corbusier Foundation (2007), (Le Corbusier, 1923-1925), Paris.

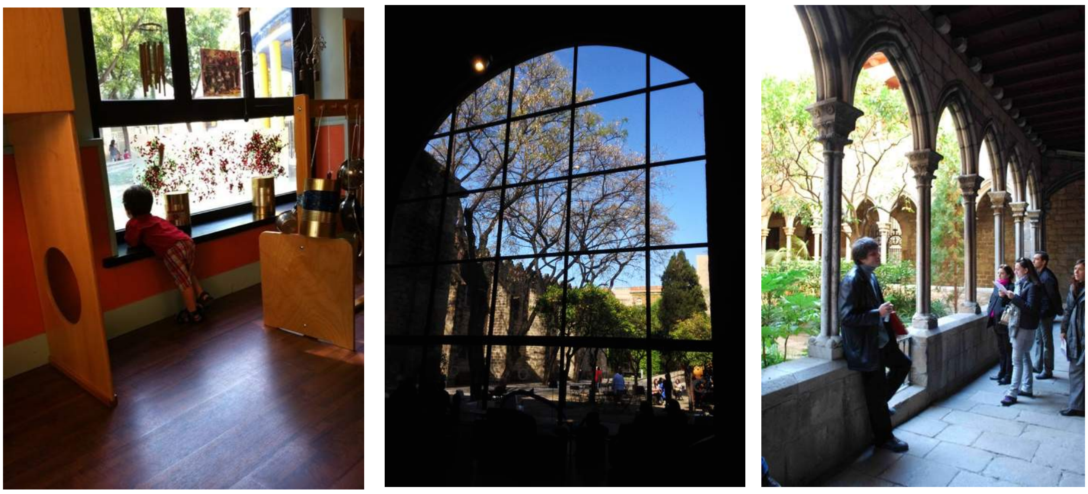

Figure 2-11. *Images showing sidelighting strategies used in different types of buildings.*

Building examples in Barcelona: unilateral window in nursery Escola Bressol Pau (2013), left. Unilateral window in Les Drassanes museum (s. XIII), centre. Santa Anna cloister (Amadeu, R., s VII), right.

Sidelighting, particularly the window, is the most used daylighting strategy in buildings, providing two main functions: natural light and views of the outdoors. Depending of windows configurations and position it could generate high contrast between indoors and outdoors by entry of direct light, sunlight and the external reflections.

Sidelighting

The side-lighting is the most common and used strategy to day-lit indoors by openings in the façade or windows. They are vertical, tilted or horizontal openings. According to their position and size, it can be also: unilateral in one wall, bilateral: two opposite walls, and multilateral.

Windows have two main functions: to provide a level of daylight, including external reflections, and, no less important, visual contact with the exterior, connecting indoors spaces with the outdoors. Appropriately designed, windows can ensure visual connections with pleasant viewings or nature, it can positively influence users' emotional or psychological situations, (Michael 2009). However, the ability of façades to distribute daylight to deep spaces is very limited, especially on cloudy skies. As a rule of thumb, windows can daylight a room to a depth of 1,5no. to 2no. times the window height above the floor (Ruck et al. 2000, Chapter 3-1).

Advanced systems as light-shelves, laser cut selective glazing, and the functional division of windows or Complex Fenestration System can satisfy several functions at the time, thermal and visual requirements, plus outdoor views (Uriarte Ortazua 2016).

Solar protection and glare control devices

The solar shading and glare protection are very different functions that require careful individual design considerations.

Glare protection has a visual function to moderate high luminances, while the solar shading has both, a thermal function and glare protection from direct light or sunlight. Solar protection and glare always are an issue for daylight, and systems and devices to protect from sunlight and glare discomfort have to be incorporated with daylight strategies, with some exceptions of oriented façades of latitude North and without direct light (Ruck et al. 2000).

Solar and glare control devices, for example, can be blinds, curtains, screens, louvers, baffles, overhangs, brise-soleil, selective reflectance and mirrored surfaces. Related to their position respect to the space and the opening can be interior or exterior, and linked with its performance and control strategy passive or active, static or dynamic devices.

2.1.4 Daylight in Mediterranean climates

The principal characteristics of Mediterranean climates are: the high availability of solar radiation and natural light, clear skies and the distinction of seasons, with the driest season in summer.

The daylight of Mediterranean climates could contribute to the sustainability by providing good natural light levels to buildings and at urban scale, with appropriate design strategies. In this sense, the available hours of natural light during the day, the prevalence of blue clear skies during the year and high illuminance levels on horizontal surfaces, are the most recognizable characteristics of natural light in these climates.

Furthermore, it can create a high reflected component or light reflected from outdoors, since most of pavements and façades are white, determining a very strong appearance and contrast between indoors and outdoors spaces (López-Besora and Coch 2016).

Figure 2-12. Images showing solar shading and light control devices in windows.

Movables porticoes and Mediterranean blinds in contemporary architecture: housing building in Graz, Austria, left, housing and commercial buildings in Barcelona: Casa Bruno Quadres (Vilaseca I Casanoves, J. architect, 1883) centre, and light and shadows in the façade of Mercat de Santa Caterina (Miralles i Tagliabue architects, 1997-2000) right.

Figure 2-13. Images of intermediate spaces and shading devices in Mediterranean climate: Mallorca, Lat: 39 34' N.

Shaded balcony and Mediterranean blinds, left, central patio/courtyard, centre, in Santanyi. Balconies, galleries, Mediterranean blinds, and overhangs in urban streets, Palma de Mallorca, right.

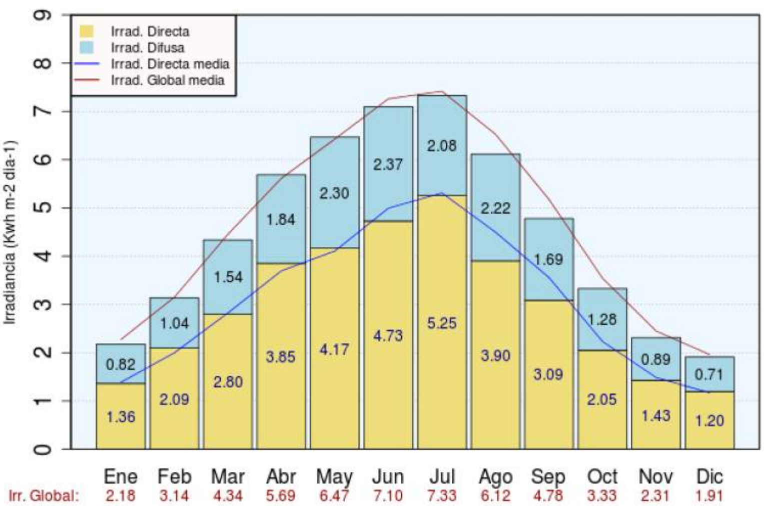

Figure 2-14. Graphic showing monthly mean values of irradiance (Kwh.m^2/day) in Barcelona: direct irradiance in yellow, and diffuse irradiance in light blue (Source: Atlas de radiación solar en España, pp.101).

Design strategies for Mediterranean climates

The solar radiation could be extreme in the summer with high direct irradiance, see Figure 2-14.

Even more important than the level of light on the work plane is the distribution of luminances and the luminance's uniformity in the FOV, which are a significant contributor to the quality of light conditions (Coch, Serra and Isalgue, 1998).

For this reason, the interior and urban spaces have to be protected by sun shading, most of all in horizontal surfaces due to the sun position during the day at noon (Zinzi et al. 2007). As well, the vertical surfaces must be protected, especially in the afternoon and evening, to maintain comfortable environmental conditions, considering temperature and light (Coch Roura 2003). The vernacular architecture, including intermediate spaces and devices to control and avoid the sun are profuse in Mediterranean architecture, such as Mediterranean blinds and galleries (Coch, Serra and Isalgue 1998), see Figure 2-13, Figure 2-16 and Figure 2-19.

As explained, in Mediterranean climate the high availability of natural light and solar radiation have to be taken into account to provide a suitable luminous environment for users. The main requirements are the following:

- Favouring the horizontal illuminance uniformity - U on the work plane by controlling diffuse and direct light, see Figure 2-16
- Preventing the risk of glare in the visual field: reducing glare sources and excessive contrast, see Figure 2-17
- Integrating solar shading and daylight control devices, Figure 2-16 and Figure 2-21

Preventing the risk of glare and excessive contrast

Daylight control and glare protection aim to reduce the vision of glare sources in the visual field and reduce excessive contrast between adjacent elements.

Integrating solar shading and daylight control devices

The main goal of integrating solar shading devices is to avoid direct light or sunlight, from high and medium angles and to control reflected sunlight from both external and internal surfaces.

The solar and shading devices can also contribute to improve illuminance levels and uniformity - U by transforming direct light into diffuse light. In the same way, to improve the contrast balance between surfaces in the visual field.

Most suitable daylight metrics for Mediterranean climates

The more suitable metrics in Mediterranean climates are those which reflect the variations of the direct and diffuse light during the day and year and consider the sky conditions, e.g.: horizontal and vertical illuminance values, sun patches and glare studies, such as DGP, DA, UDI.

The DF does not consider direct solar penetration and cannot prevent glare issues from different façade orientations, due to the fact that it must be obtained in overcast sky conditions. In this particular study, this type of sky has a lower incidence, as in the case of Mediterranean climates. However, it is a useful metric for making comparisons between buildings and is the most used metric in current regulations, when minimum daylight levels are established.

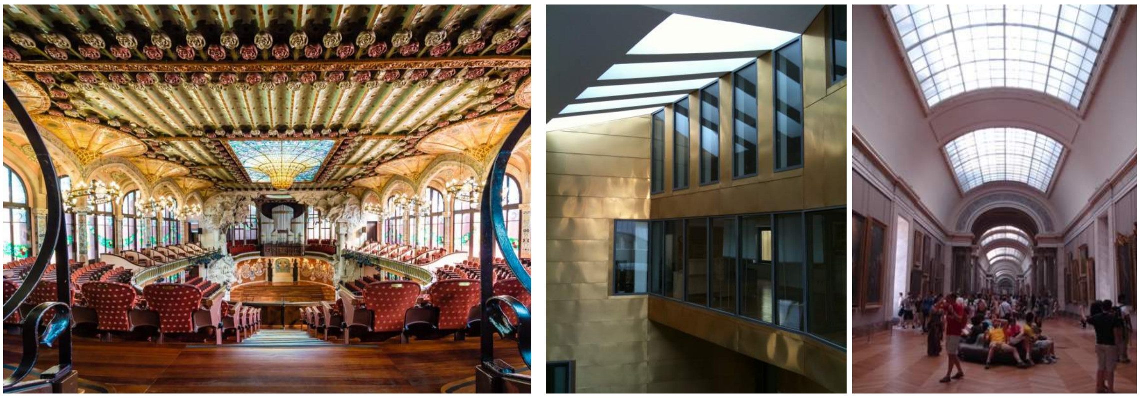

Figure 2-15. Images showing toplighting design strategies with roof lights in concert hall, theatre- music school and museum.

Palau de la Música Catalana (Source: ©Mateo Vecchi, https://www.palaumusica.cat/es/sala-de-conciertos_550481) in Barcelona (Domènech i Montaner, L.,1905-1908) left: the magnificent roof light, representing the Sun, is positioned in the centre of the space to daylit the concert hall plus bilateral windows. The translucent coloured glass is to maximise the light diffusion. L'Atlàntida theatre and music school in Vic (Llinàs, J., 2010), centre: the atria with a central skylight is potentiated with the internal specular reflections of side walls, covered with cooper finishing. Palais Royal- Musée du Louvre in Paris (s XII), right: the lineal central roof light is used to daylit with diffuse light the painting' collection expositions in the Richelieu and Denon wings.

Figure 2-16. Images showing the use of the traditional Mediterranean blind in Barcelona.

Casa Josep Coll in Hostafrancs (Masdeu Puigdemasa, J., 1910), left. Casa Roviralta in Sant Gervasi (Rubió i Bellver, rebuilt 1903-1913) centre. Housing building in Barceloneta (Coderch, J. A. & Valls, M., 1951-1955) right. The louvers have different positions, which are capable to re-direct the daylight according with the visual requirements and position of the sun.

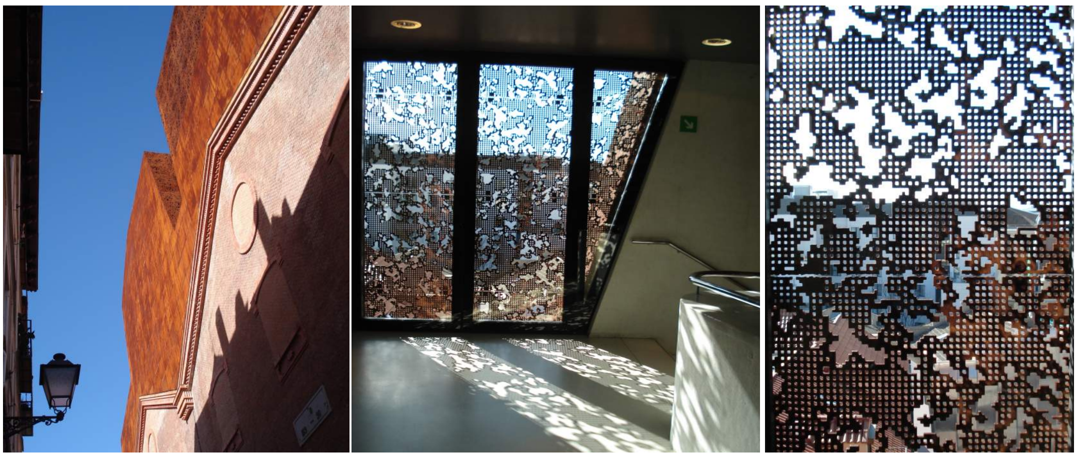

Figure 2-17. Images showing the use of an external perforate screen in windows to filtrate the sunlight.

La Caixaforum Museum building (Herzog & De Meuron, rebuilt 2008) in Madrid: a view from the outside, left. The view from indoors and screen detail, centre and right. The sunlight is filtered and the contrast luminance between the window and the adjacent wall has decreased by a perforated screen.

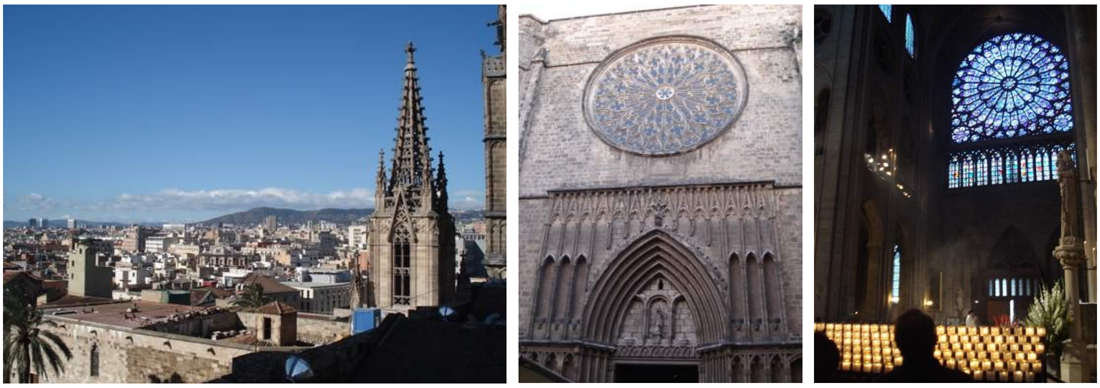

Figure 2-18. Exterior and interior views of large windows and clerestories in gothic cathedrals.

The tower of Santa Creu i Santa Eulàlia (1429), left. The exterior of the rose window in the front façade of the Basilica de Santa Maria del Pi (S. XIV), centre. The North rose window of the Notre Dame Cathedral (1250), right.

The rose window decomposes large glazing areas into small portions and parts. The use of colourful finishing and the intricate division pattern, decreases the contrast between the opaque and translucent surfaces, filtering and colouring direct and diffuse light. However, from an indoors view, there is a high contrast between the massive dark walls and the openings from the top of the space, with very low natural light hitting the interior surfaces, that potentiate the symbolism and theatrical effect of daylighting: the "divine" light filling the space.

Figure 2-19. Examples of windows with shading devices in Tunisia.

Examples showing the use of Mediterranean blinds and screens (wooden jalousie, lattice, trellis) to filter out daylight: house balcony and windows in Sousse, left; and window in Museum of Villa Sebastian in Hammamet, centre and left.

From the exterior, the screens look like an opaque material, but from indoors the view is completely different, it appears as a translucent surface.

Figure 2-20. Images of the use of roof lights in Museums, with internal louvres and baffles, and artificial light.

MAXXI Museum in Rome, IT (Z. Hadid & Partners, 2009), left; The Victoria & Albert Museum in London (F. Fowke, 1853-1862 and refurbishments in 1899, 1909), right (Source: https://www.vam.ac.uk/event/py6v0By7).

Day and night appearance of top-lit spaces and the use of blades, louvres and baffles as solar protection devices. Moreover, the artificial light is integrated into the ceiling and it is used to emphasise architectural elements, in this case the interior baffles and the staircase (MAXXI Museum).

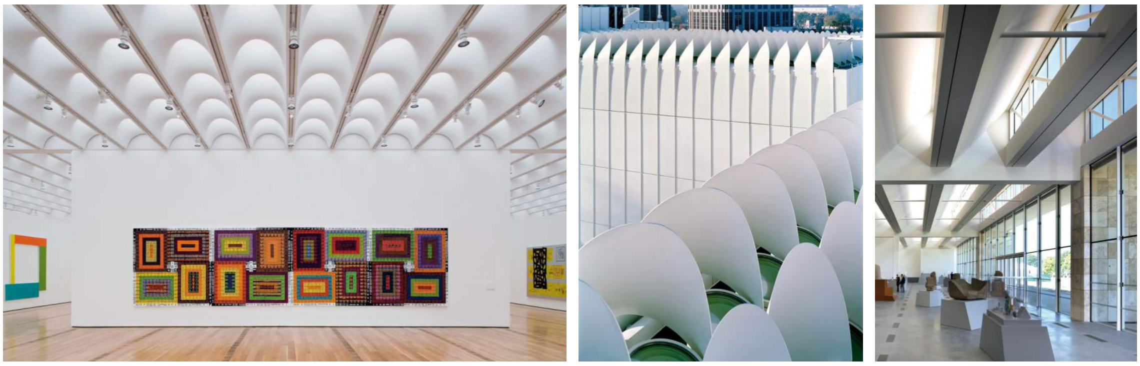

Figure 2-21. Images of examples of daylight strategies with toplighting and sidelighting systems in museums.

High Museum expansion in Atlanta, USA (Renzo Piano Building Workshop 1999-2005,) left and centre, (Source: ©Michel Denancé, http://www.rpbw.com/project/high-museum-expansion); and The Resnick Pavilion in Los Angeles, USA (Renzo Piano Building Workshop 2006-2010), left (Source: ©Nic Lehoux, http://www.rpbw.com/project/the-resnick-pavilion-lacma-expansion-phase-ii)

Toplighting systems implemented in museums require diffuse daylight with special care of uniformity, and minimizing, as well, sunlight penetration and glare.

Naranjos in Santa Anna cloister in Barcelona (Amadeu, R., s VII), left. Reflection (Regent´s canal, London, 2020), centre. The pink sunset clouds (Hackney, London, 2020), right.

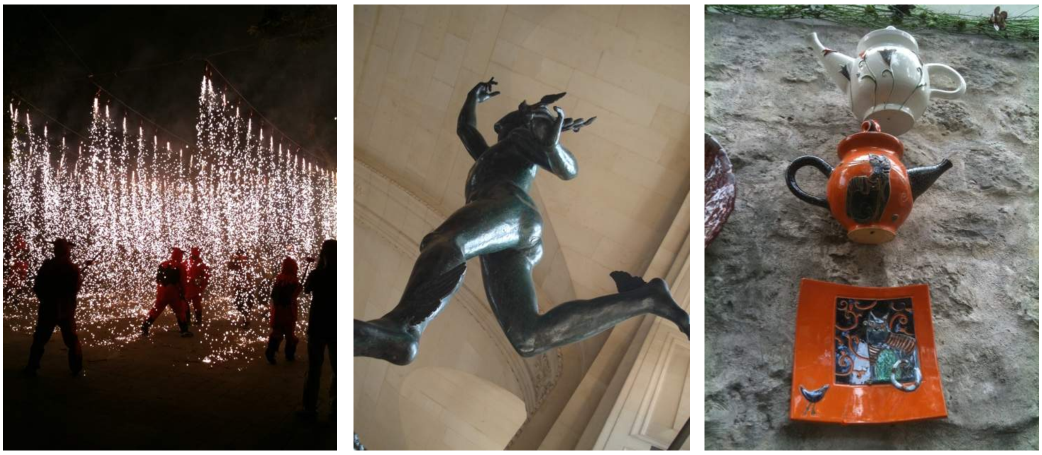

Figure 2-22. Images showing the light interaction with the objects and their environment.

The Correfocs de Sants in the Plaça d' Osca at night, fireworks during the festivities of Barcelona city, left. Mars statue in the Louvre Museum under daylight, centre. Handmade ceramic objects displayed in the street façade in Santanyi, Mallorca, right.

The light and its interaction with objects, indoors and outdoors environments is defining the visual perception, creating brightness, shadows and contrast. These allow to the observer to perceive shape, contour, volume, colour, materiality, spatiality and distance, among others.

2.2 Visual comfort

The environmental comfort, in general, depends on many parameters, such the user's characteristics, as psycho-physical: age, gender, general and particular health conditions, mood, expectations, among others. It is also influenced by the user' interaction with the stimuli of the physical environment or environmental conditions (Isalgue et al. 2006).

The relationship between the users as individuals, and the physical environment is a complex issue. Notably, most of all in working activities, the user or occupant becomes conscious of the physical environment when it is uncomfortable (Nazzal and Chutarat 2001).

Lighting, both natural and artificial light, is one of the defining factors in the way of users perceiving the space and therefore, defining the users' experience and their response to perform different activities.

In particular, the visual comfort depends on the user and their interaction with the luminous environment, during the performance of the visual task or activity, under daylight and/or artificial light.

The European standard UNE-EN 12665:2011 defines visual comfort as "a subjective condition of visual well-being induced by the visual environment" while the observer is performing a visual task, and basically it depends on:

- The physiology of the human eye, and psychology of the observer or user: the visual perception
- The physical quantities describing the amount of light and its distribution in the space: the luminous environment, see section 2.1.3
- The spectral emission of the light source: the quality and quality of light, see section 2.1.3

Thus, not just the illuminance level is needed, but also the limiting discomfort glare and minimum colour rendering index of the source. Particularly the colour rendering and colour temperature of light are most relevant in artificial lighting, but also in daylight conditions, due to the light source, time and sky conditions, and different glazing could modify the colour temperature.

The lack of visual comfort or visual discomfort may have negative repercussions on users' experience, and may also disturb their health. In this sense, in the playing area or court, there might be situations where daylight can cause, by too much or too little, situations of visual discomfort to users, where their visual task performance could be compromised.

The discomfort and disability glare could be critical issues for the sports' practice, when affecting the users: athletes, spectators and broadcasting television conditions- TV.

In this work, the study focuses on the visual comfort of sports users under daylight conditions. However, evaluating and establishing visual comfort conditions within a real luminous environment is a complex task, considering that both objective and subjective parameters should be taken into account for the user's satisfaction, see section 2.2.5 below.

2.2.1 Visual system and visual photo-reception

The visual system is part of the central nervous system and gives to humans the ability to process visual information or visual details. The visual system carries out several and complex tasks, that involve: the reception of light through the eyes, forms of monocular presentation on the retina, and the construction of binocular images in the brain, after it was transported by pathways as the optical nerve.

Adaptation

The human eye adapts to the average luminance of the object or target and its immediate surroundings in the visual field. The eye is capable of adapting to a wide range of luminances, from 1×10^{6} to 1×10^{-6} (Jacobs 2003; 2004). There are two different photoreception cells responsible of adaptation in the retina, which activate and response according to light levels, adjusting the sensitivity of the visual system: rods and cones.

The cones are responsible for giving us colour vision and visual acuity, and the roads for the peripheral vision. Also, the eye pupil either constricts or dilates to regulate and protect the retina from high intensities of light (Pierson et al. 2018).

The visual system has the capacity to adjust over an enormous range of light intensities, from very low to very high luminance levels and viceversa. The adaptive processes to match the ambient illumination are: light adaptation, that refers to an adjustment to higher levels, and dark adaptation to and adjustment to lower levels or darkness (Reeves 2009).

Above a certain luminance level, about 0.03 cd/m2, the cone mechanism is more active or photopic vision. Below this level, the rod mechanism comes into play providing scotopic or night vision. The range where two mechanisms are working together is called the mesopic range.

There is a certain time, that is needed to allow the eye to adjust to the lighting conditions, called the adaptation time. Since this phenomenon is very important to consider the minimum time required and the sense of the adaptation eye process: from high to low luminance or dark adaptation, and from low to high luminance or light adaptation. Furthermore, dark adaptation time is significantly longer than light adaptation, and it could require from 10 up to 60 minutes to fully adjust (Jacobs 2003; 2004). In this sense, it must be noted that the eye's adaptation is faster from low to high luminances, rather than from high to low. As a result, objects and surfaces can be not seen properly because they are out of limits of the eye adaptation, above or below. The observers also can experience visual fatigue.

This phenomenon is extremely important in dynamic visual tasks and sports activities because if there are high differences between maximum and minimum luminance values, when following a moving target, the eye is not capable to rapidly adapt, so objects and surfaces could be out of range to be seen.

Moreover, the visual system has the capacity to adapt to different light sources and colour temperatures. This process is called colour adaptation and is responsible to allow the accurate judgement of colours.

Visual Field or Field of View- FOV

The Field of View - FOV is composed by different reflections and transmission of light from the environment. The ratio between illuminance levels, reflectance and transmittance coefficients, created a visual sensation in terms of subjective brightness of different elements or a comparison of diverse luminance values.

The FOV is that part of space which can be seen by the observer, see Figure 2-23, involving head and eye movements, and measured in angular magnitude (Panero and Zelnik 1996). It can be also divided into monocular and binocular vision. The monocular vision is the visual field of the individual eye, and the binocular is the central visual field of both eyes created by overlapping each eye visual field, according to the next:

- Monocular vision: the images transmitted are not sharp, so the objects appear diffuse and not defined.
- Binocular vision: is the seeing of the portion of space where the fields of the two eyes overlap.

In the visual field, the foveal and peripheral vision can be distinguished. According to Rea (1999) (cited in Inanici 2005b) "foveal vision is the seeing of objects in the fovea, which is approximately the 2° in the central part of the visual field. It permits seeing much finer detail than does peripheral vision. Peripheral vision is the seeing of objects displaced from the primary line of sight and outside the central visual field".

Furthermore, the human visual system has diverse sensibility to luminance differences in the FOV. Accordingly, it can be very sensitive to low luminance values in the foveal or accurate area of vision: 1°- 2° of the visual task, see *Figure 2-25*, but insensitive to large luminance differences in the peripheral regions of the FOV >60°, see Table 2-1.

Likewise, the contribution of luminances in the visual perception has different magnitudes as reflected in Guth's position index (cited in Jakubiec and Reinhart 2012), increasing the position index' value if the object moves further from the centre of the view, towards the upper or lower visual field, see *Figure 2-27*.

Visual perception

Visual perception is the psychological ability that is composed by receiving the visual information through the eyes and involves complex mechanisms performed by the brain. Based on the previous experience, cultural heritage and memory, the brain processes the visual stimulus collected by the eyes and translate this to significant information to the observer, among others, for example the following:

- Identification and categorization of visual objects
- Colour, shape, and contour recognition
- Sense of the space, as orientation and spatiality
- Sense of the time, as morning, noon, evening, night
- Assessment of distance
- Face recognition
- Danger situations

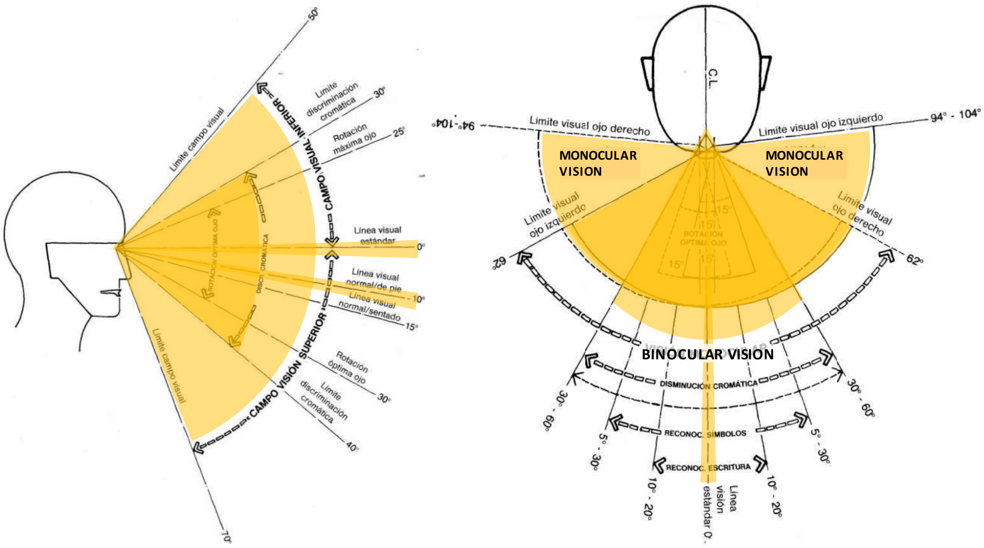

Figure 2-23. Schemes of visual field in the vertical plane (left) and horizontal plane (right), with highlighted regions: accurate area of vision, limit of colour recognition and visual field limits (Source: Panero and Zelnik 1996, pp. 287).

Visual field	
Line of sight	h: 0º v: 0º- 10º
Accurate area of vision	h: 1º- 2º v: 1º- 2º
Limit word recognition	h: 10º- 20º v: 20º
Limit symbols recognition	h: 5º- 30º v: 30º
Limit of colour discrimination Upper limit Lower limit	h: 30º to 60º v: 30º v: 40º
Binocular vision Upper limit Lower limit	h: 0º- 62º v: 0º to 50º v: 0º to 70º
Visuald field limits Left and Right eye limits Upper limit Lower limit	h: 63º to 94º-104º v: 50º v: 70º

Table 2-1. Visual field of view by regions of interest with vertical and horizontal angles, according to Panero & Zelnik, 1996, based in schemes of visual field shown in Figure 2-23.

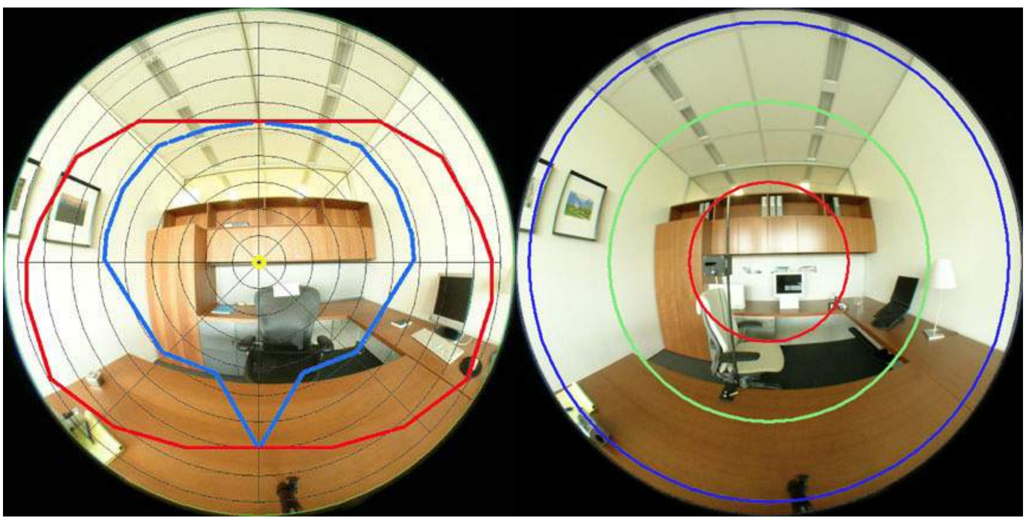

Figure 2-24. Fish eye photographs showing the user visual field, when the observer is looking towards the front in an office space, with equidistant projections of 2°, 30°, 60° and 90° in diameter (Source: Inanici 2005b, pp. 25, 26).

Colour

The perception of colour, in humans, is a psychological response that involves the physical reaction of the eye and the interpretive response of the brain to wavelength and brightness of light. So, is not an objective component and derives from the stimulation of the photoreceptor cells by wavelength of light.

The colour of surfaces is a combination of the spectral reflecting properties of the surface, as light absorption or reflectance, shape, roughness and emission spectra or colour, and the spectral composition of the light sources (Jacobs 2004). The light source properties depend on intensity, directionality, colour rendering index, and colour temperature. So, colour is the result of spectra of optical radiation generated by light sources, modified by objects and processed and interpreted by the human visual system (IES 2011, pp 6.1).

The RGB colour is one of the most well-known systems and responds to the human tri-chromacy or three cone cell types in humans, responding to the three bands of light: red 564-580nm, green 534-545nm and blue 420-440nm. Also, the CIE standard colour space (CIE 1931, cited in Jacobs 2004) is based in the tri-stimulus of XYZ coordinates, based in the response curve on the human eye, Y curve.

Subjective brightness

The visual field is composed of different reflections and transmission of light. The ratio between illuminance levels and reflectance and transmittance coefficients, created a visual sensation in terms of subjective brightness of different elements by comparison of diverse luminance values.

Brightness is the visual sensation by which an observer registers the degree to which a surface appears to emit or reflect more or less light. This subjective sensation cannot be measured in absolute units and it describes the appearance of a source or object (Ruck et al. 2000).

Visual task

The visual task is the term given to an activity which requires the visual perception of the observer, in a specific area or visual task area. This term designates those details and objects that must be seen in the performance of a given activity, including the immediate background of the objects (IES 2000).

The visual task area is the partial area where the visual task is performed. For example, in offices, the visual task area is the partial area at the workstation where the visual task is being carried out (EN 12464-1).

Visibility of the object

The visibility of the object of interest, during the visual task, depends in many instances, on the way in which the light is applied, the colour characteristics of the light source and surfaces, and the amount of glare the system gives. Therefore, depending on visual task performance, a suitable lighting has to provide:

- Firstly, the provision of adequate levels of illuminance E_h and E_v on the task if is necessary
- Secondly, quality parameters as colour rendering, limitation of glare, contrast and luminance distribution within surfaces and objects are also required

Visual Field of Vision	
Centre of visual task Foveal vision 100% Visual acuity	h: >0º <2º v: >0º <2º
Near peripheral Binocular vision	h: >2º <30º v: >2º <30º
Mid peripheral Binocular vision	v: >30º <50º-70º h: >30º <60º
Far peripheral Monocular vision	v: >30º <50º-70º h: >60º <100º-110º

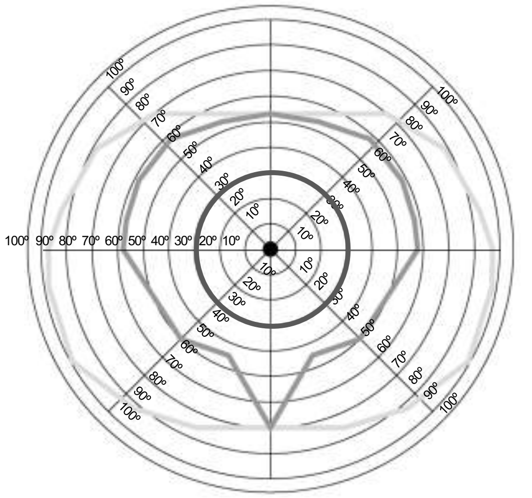

Figure 2-25. Table and graphic with the regions of interest in the field of view- FOV, related to the visual task (based on Inanici 2005b, pp. 25) see Figure 2-24: foveal, near peripheral, mid and far peripheral.

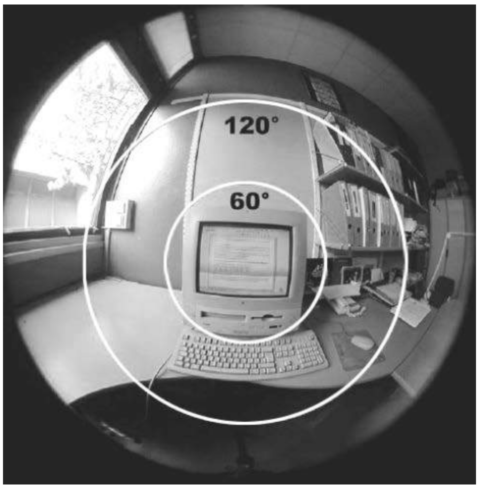

Figure 2-26. Regions of interest in the visual field: ergorama (60°) and panorama (120°) (Source: Sutter, Dumortier and Fontoynont 2006 cited in Dubois et al. 2016a, pp. 38)

Note that the real panorama or mid peripheral vision, is usually not perfectly circular due to the presence of the nose, which cuts off a part of the lower visual field. In addition, the shape of the external limit of the visual field is usually not a perfect circle since the field is normally slightly larger than high due to the fact that we have two eyes (Dubois et al., 2016).

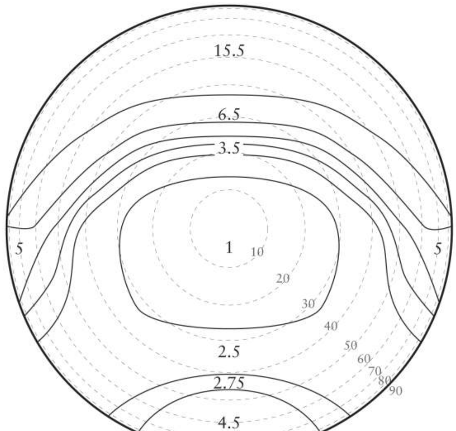

Figure 2-27. Selected Guth's position index values plotted on top of 180° hemispheric view projection (Source: Jakubiec and Reinhart 2012, pp.4)

The solid lines indicate major division of values of Guth index and dashed lines indicates the angle between the view centre and an object.

2.2.2 Visual discomfort

Accordingly, to the visual comfort definition described above, visual discomfort is the contrary, a subjective condition where there is a lack of comfort to see the target or the object and details of interest by the observer. There is a decrease in the visibility of the object of interest and therefore of the visual perception.

Furthermore, there is a widely shared notion that E_h horizontal work plane illuminance as a quantitative parameter, which is easy to measure, is a poor predictor of discomfort glare. The amount of light hitting a working surface has little in common with an observer's visual experience of a space. Instead, glare analysis should be based on the luminance distribution in the field of view of an observer/user.

Nowadays, a robust agreement exists about that glare is one of the major factors affecting visual comfort (Painter et al., 2009, Pierson et al., 2018) but there are other factors interacting that should be considered, see section 2.2.5 below.

To resume, the identification of glare sources, in terms of luminance or brightness, its position related to the line of vision, in terms of solid angle and size, and the luminance or brightness to which the observer' eyes are adapted, are very significant parameters to describe visual discomfort situations for users.

2.2.3 Glare

According to that, glare is a condition of vision which there is discomfort with different magnitudes to perform the visual task, or a reduction in the ability to see details or objects in the visual field, caused by:

- Unsuitable range of luminances or luminance distribution
- Extreme or excessive contrast
- Veiling reflections, brightness

Another definition of glare is: "that light within the field of vision that is brighter than the brightness to which the eyes are adapted" (Reinhart and Wienold 2011). Furthermore, glare depends on the position and user's view-direction within a space, rendering it difficult to assess compared to conventional illuminance-based metrics (Jakubiec and Reinhart 2012).

Disability glare

The disability glare or contrast effect, which impairs the vision of objects and details, or the inability of a person to see certain objects in a scene, without necessarily causing discomfort. In this case, the luminance of the source is the major contributory factor. Furthermore, it can cause considerable discomfort when people are exposed to high luminance sources for long periods of time.

Discomfort glare

Discomfort glare causes an annoying sensation without impairing the vision of objects and details (CIE 1983). Also, it can be described as the premature tiring of the eyes due to glare (Reinhart and Wienold 2011).

The discomfort glare could be described as follows:

- Saturation or absolute glare: the total amount of light reaching the user' eyes is too large
- Contrast or relative glare: a strong contrast between the viewing direction and a bright spot in the visual field of view or the contrary, a bright environment while the visual target is perceived too dim

The discomfort glare produced by and individual source (CIE 112-1994) mostly depends on:

- $L_s =$ Source luminance in the direction of the observer's eye
- $\omega_s =$ Solid angle subtended by the source at the observer's eye
- $\theta \;=$ Angular displacement of the source form the observer's line of sight
- $L_f =$ General field luminance controlling the adaptation level of the observer's eyes

2.2.4 Daylight discomfort glare

The daylight that reaches the eye of the observer from the side windows and top-light openings, could affect the visual task causing discomfort glare, without impairing the vision of objects, and even disability glare, causing the entirely reduction in the ability to see for a determining period of time.

According to different authors (Pierson et al. 2018a), there is not only one way to quantify visual discomfort in buildings from daylight. No current indices can properly explain the high variability existing between individuals' discomfort glare perceptions, provoking an irritating or distracting effect. Additionally, the perceived glare with sunlight, present in real environments, is lower than theoretical calculations (Atif et al. 1997; Aguilar Sanchez 2014). This can be attributed to the positive effects of sunlight in real environments (Inanici 2005b).

The first equation to describe the degree of perceived discomfort glare from windows and modified later becomes the Daylight Glare Index- DGI (Hopkinson 1972; Chauvel 1982, cited in Person et al. 2018a) see Equation 2- 4. The DGI delivers a value between 16 or just imperceptible, and 28 or just intolerable.

$$DGI = 10\ log_{10}\left[0.478\sum_{i=1}^{n}\frac{L_{s,i}^{1.6}.\,\omega_i^{0.8}}{L_b + 0.07\omega^{0.5}.\,L_{win}.\,P_{\ i}^{1.6}}\right]$$

Equation 2- 4. Daylight Glare Index- DGI equation. (Source: Hopkinson 1972, and Chauvel 1982, cited in Pierson et al. 2018a, pp.3).

Where:

$L_{s,i}$ = the luminance of the glare source(s) [cd/m^2], ω_i= solid angle of the source(s), L_b = the luminance of the backroung [cd/m^2], L_{win} = the luminance of the window [cd/m^2], P_i = the position index relative to the glare source (s)

Numerous field studies of discomfort glare suggested that E_{veye} vertical illuminance at the observers' eye level is a good indicator of glare from daylight, at least for workplaces where daylight is dominant (Reinhart and Mardaljevic 2006; Wienold and Christoffersen 2006).

There is presently no standardized formula for calculating discomfort glare from daylight, but the application of the Daylight Glare Probability- DGP calculations is a reasonable approach for office environments (Dubois et al. 2016a).

Daylight Glare Probability - DGP

DGP is a recently proposed discomfort glare index (Wienold and Christoffersen 2006) that was derived from laboratory studies in day lit spaces using seventy-two test subjects in Denmark and Germany. The scale of the DGP index, compared with the subjective ratings obtained, varies from: DGP <0,35 is perceived “imperceptible glare”, 0,35-0,40 is “perceptible”, 0,40-0,45 is disturbing, and DGP >0,45 is “intolerable” (Wienold 2009).

The DGP is defined by the following equation:

$$DGP = c_1 . E_v + c_2 . log(1 + \sum_i \frac{L_{s,i}^2 . \omega_{s,i}}{E_v^{a_1} . P_i^2}) + c_3$$

Equation 2-5. DGP - Daylight Glare Probability formula (Wienold and Christoffersen 2006).

Where:

E_v =vertical illuminance at the eye [lux], L_s = luminance of the source [cd/m2], ω_s= solid angle of the source [sr], P =Guth position index.

The DGP includes the absolute term, which represents the absolute glare with the E_v vertical illuminance at eye level. The second term depends on the detected glare sources in terms of size, luminance and position (Wienold and Christoffersen 2006; Wienold 2009). Two methods are also derived from the DGP for dynamic calculations: the simplified or DGPs and the enhanced simplified DGP (Wienold 2009). Since the DGPs is based on the vertical eye illuminance only, the value can be easily calculated by DAYSIM software (NRC ISE 2012, Version e3.1 Beta):

$$DGPs = 6{,}22 . 10^{-5} . E_v + 0.184$$

Equation 2-6. DGP – Simplified Daylight Glare Probability- DGPs formula (Wienold 2009).

Where: E_v = vertical illuminance at the eye [lux]

Discomfort glare perception

Some of the factors influencing discomfort glare perception from daylight are still unknown and the mechanism and the interactions between them behind the discomfort glare process is not well understood (Pierson et al. 2018a). More research is needed in this sense, to explain the high variability existing between individuals’ discomfort glare perception, taking into account that the physiological and psychological factors could be involved and influence the visual discomfort perceived by the observer.

Moreover, no exact correlation should be expected between discomfort glare assessed by an index and the perceived by subjects.

Related to the lighting and the lighting environment, the two major variables of discomfort glare are the Luminance of glare source L_s [cd/m^2] and the Adaptation level, as vertical illuminance at the eye $E_{V\ Eye}$ [lux] and the background luminance L_B [cd/m^2].

Luminance of the glare source- Ls

The luminance of the glare source is one of the major variables of discomfort glare as the source intensity [cd/m^2] in the observer viewing direction, but is not the only variable to predict the visual discomfort due to daylight glare. Other factors should be considered, as the adaptation level.

When studying daylight glare (Pierson et al. 2018a), it is important to pay attention considering “the source” as the luminance of the sky patch through the window, the luminance in the centre or the luminance average of the window. Moreover, the non-uniformity of the window luminance should be taken into account. Currently, glare sources in daylight conditions are generally defined as the bright spots in the FOV and considering the task-threshold area, as for example, which ones that exceeding four times the task area average illuminance (Wienold 2009) or seven times higher through Findglare (Ward 1993).

Adaptation level

The adaptation level can be defined as the light level in a room in which the observer’s eyes adapts, regulating the amount of light coming on the retina. The effect of two very different ranges of luminances, one very high and the other very low, can generate discomfort and visual fatigue by adaptation, especially in the focus and the immediate surroundings of the visual field of the users.

Furthermore, the duration of exposure to a glare source has an influence on the discomfort glare perception, increasing the discomfort in very short exposures rather than continuous or longer exposures. This could be explained at the very short adaptation time (Hopkinson 1957; Iwata et al. 1990, cited in Pierson et al. 2018a).

The two factors to evaluate the adaptation level are the vertical illuminance at the eye $E_{V\,Eye}$ [lux], as in the DGP formula (Wienold and Christoffersen 2006), and the background luminance, L_B [cd/m^2]. The background luminance is interpreted by many authors as the average of the visual field excluding the glare sources, but others included the glare sources on it.

About the interaction between the observer and the glare source, the more influential factors are the size of the glare source and the position of the glare source, as seen by the observer. This is particularly important when the user interacts actively with the space and there is more than one viewpoint and work plane defined.

Size of the glare source as seen by the observer

The size of the glare source as seen by the user, although it is not clearly defined, is described by the solid angle which expresses the width of the source as it appears to the user’ eyes. In this sense, the distance from the window or the glare source, is therefore impacting the way discomfort glare is perceived. Consequently, the further away from glare source, the lesser is the perceived discomfort glare because of the solid angle (Pierson et al. 2018).

Position of the glare source as seen by the observer

The position of the glare source (index P by Lukiesh and Guth, cited in Pierson et al. 2018a) and linked to the observer’s line of vision, is also considered an influencing factor in discomfort glare, according to the fact that the further the glare source from the line of vision, the less the perceived discomfort. Presently, Guth’s position index is used in most glare metrics, see Figure 2-27).

Related to the context or the environmental characteristics of the space, the most significant factors are the spectrum and colour temperature, the view-direction and observer position.

Spectrum and colour temperature

Although more research in this field is required, the colour temperature of the light could have an impact on discomfort glare perception, as demonstrated by the blueish light or glare sources with short-wavelengths are perceived as more discomforting (Pierson et al. 2018). Also, glazing that filters some parts of the light spectrum causing it to appear coloured might have an influence on daylight discomfort glare.

View direction and observer's position

The luminance distribution across the FOV changes depending on the view direction and the position of the observer, so the surfaces' reflectance and the background are varying with their movement, which comprise for example, head and body. Its influence in discomfort glare perception has been studied (Hiring et al. 2016 and Sekihara et al. 2016, cited in Pierson et al. 2018a), but in static environments and visual tasks.

Furthermore, the adaptive comfort zone concept was developed (Jakubiec and Reinhart 2012) which accounts that users tend to adjust their view-direction to avoid glare sources. However, these studies are not fully suitable for sports activities, where the occupants have a dynamic visual task and there is no possibility to choose their view direction during the action (athletes and spectators), plus the background environment is 360°.

Furthermore, authors suggested that the prediction on visual discomfort should integrate several metrics and experimental surveys to cover all situations and validate glare assessment methods according to the environment and the visual task performed (Jakubiec and Reinhart 2012; McNeil and Burrell 2016).

2.2.5 Visual perception of day-lit architecture

Patterns created by daylight can affect the users' perception of the architectonic space, as the spatial complexity, the aesthetic judgement, and orientation, for example. Architects and designers have been using daylight, in particular sunlight, to create emotional effects in the building's occupants (Ruck et al. 2000, Chapter 3-1).

Recent studies considered the perceptual performance of the architecture, both interior and exterior, which can be modified by the quality of daylight (Rockcastle and Andersen 2012). For example, sunlight can intensely change user's perception of interior architecture.

Therefore, there are studies to develop a language of contrast typologies related with daylight design strategies, explaining different perceptual luminosity within the space. According to a study, a range of ten typologies has been established to represent a range of architectural examples to show how daylight impacts in the user's perception of interior spaces through luminous effects. The scale varies from 1, maximum of spatial contrast and temporal variability from direct light, to 10, minimum and low contrast and temporal variability with diffuse light, see Figure 2-28. The conclusions shown that the composition of light and shadow is the key factor which create an impression of contrast within each image, rather than the average of brightness or range of luminance values.

Even though this specific matter is not evaluated in this thesis, about the perceptual performance of the architectural spaces under daylight, it can be very useful for explaining typology models in terms of spatial contrast, temporal variability and dynamic luminous effects and users' visual comfort preferences. Particularly, in this thesis, to be linked to the users' preferences results with different daylight design strategies and its performance in sports halls.

Perceptual performance indicators

The perceptual daylight indicators are composed of studies related to the user or occupant-preference to perceptual factors, such as brightness, contrast and luminous diversity, within the user's FOV and related to the visual task. The objective of these metrics is to expand the understanding in quantifying the perceptual effects in users of luminous composition in architecture (Rockcastle and Andersen 2012). In this sense, more experimental methods were carried out to compare subjective ratings of daylight composition in architecture against quantitative or contrast metrics, to understand the correlation of sun position, spatial composition on subjective ratings (Rockcastle and Andersen 2015).

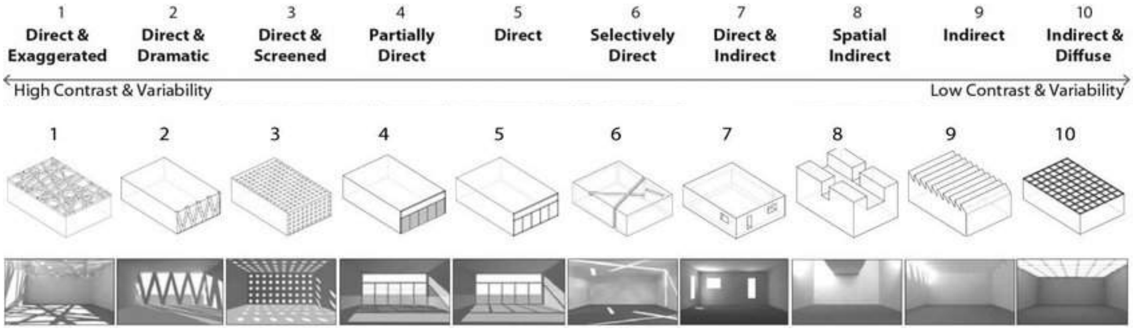

Figure 2-28. Matrix showing 10 typological models according with daylight dynamics perception.
High spatial Contrast & Temporal variability (1) on the left, to Low Spatial Contrast and Variability (10), on the right (Source: Rockcastle and Andersen 2012, pp. 5-6)

Luminance distribution: uniformity, mean and maximum values

The luminances in the FOV are a significant contributory factor in the visual perception of the luminous space: reflected light from surfaces and objects reaching the observer's eye.

An adequate amount of variation in luminance values assures visual comfort, visibility, and aesthetically pleasing environment. The quantities that differ significantly from the average or target values may indicate poor lighting conditions (Inanici 2005b). The spatial distribution of light can be measured as luminance and/or illuminance variations across a plane or surface. The maximum, minimum, and average values can be extracted and calculated using different techniques, such as per-pixel data acquisition.

Luminance values are considered important in the analysis of visual comfort, since they represent the amount of light that affects the user's visual system, in other words, the light that is seen by the observer or user, according to the quantity and the angle of incidence. This technique is convenient for studying the luminances values and distribution within the whole scene (e.g. circular part of the fisheye), a surface (e.g. architectural element such as floors, ceilings, walls, openings, etc.), or a region of interest, such as a task area or specific part of a human visual field of view (Inanici 2005b), see section 2.2.1 above.

When it is difficult or impossible to precisely what consists the immediate and remote surroundings, as in this study in particular, the luminance within the ergorama and panorama should be measured instead (Dubois et al. 2016a). The ergorama is a cone of 60°, centred about the main line of sight. The panorama is a cone of 120-140° centred about the line of sight, see Figure 2-26 (Meyer, Francioli and Kerhoven 1996, cited in Dubois et al. 2016a).

In the particular case of sports' users, due to the visual task being performed in an open space (i.e. the playing area or court that is not delimited), the luminance contrast, luminance ratios (Ding 2017) and the evaluation of visual field of view (Inanici 2005b; 2010) can be considered in the assessment of the visual comfort.

Luminance ratios and contrast

The luminance balance in the field of vision should not exceed certain thresholds to avoid the possibility of glare by excessive contrast.

Maximum luminance ratios of 1:3 in the ergorama and 1:10 in the panorama should be respected (Meyer, Francioli, and Kerhoven 1996, cited in Dubois et al. 2016a). In this sense, studies show that contrast above 0.4 (1/40) can be chosen as a minimum design goal in offices, in static visual task.

In daylight conditions and performing low visual tasks it can be extended up to 1/100, between task and maximum value, distant surroundings and background (Ding 2017).

2.3 The luminous environment: the sports halls

Practicing sports in indoor spaces require the achievement of certain values of the environmental parameters, in this particular case, of the minimum requirements for visual comfort.

In this study, the analysis of the luminous environment is carried out in sports hall buildings, in particular, in the court or field of play and the surrounding spaces, including architectonic elements, as ceiling, interior façades, floors, and the spectator's or audience' seating area.

In the sports halls, in general, all the architectural elements materialize the luminous space or environment where the visual task is performed by the user.

Taking into account that there are multiple working planes both horizontal and vertical, the following should be especially considered for the design of the sports spaces:

- The sports track or court
- Ceiling, walls and interior enclosures, steps, access doors to the track and to the stands
- The top and side openings to daylight the court, in the first place, and the surroundings and distant environment, in the second place
- Exterior walls and facades, doors and adjacent spaces

Figure 2-29. Time frame summary of relevant facts in Modern Olympic Games based on available data: the presence of remote audience and TV retransmission, building environmental comfort features and generations of sport halls based on (Sheard 2001).

2.3.1 Sports hall architecture

Sport is "an activity involving physical exertion and skill, esp. (particularly in modern use) one regulated by set rules or customs in which an individual or team competes another or others", "an occasion on which people compete in various athletic activities or other sporting activities", and "an activity providing diversion, entertainment or fun; a pastime" (Oxford English Dictionary-OED 2020). According to that, the practice of sports implies a physio-activity performed with different skills and efforts of elite athletes or general public of all ages, for competition and/or entertainment and leisure purposes.

In recent years, the physic-sports practice has become a universal social phenomenon and it is an instrument of relation and of integration of people, according to the Master Plan for Sports Facilities -PIEC[6] elaborated by Consell Catalá de l'Esport - CCE (Generalitat de Catalunya 2005a).

Most sports originated in the days before effective artificial light was available, so they began practicing outdoors. Many sports palaces and sports fields today still have natural light during the daytime. However, due to the functional requirements and the continuous use, other spaces can be functioning independent of daylight and climatic factors, such as cold, rain and heat. Consequently, they have been transformed into covered or indoor spaces.

The origins of the indoor sports halls result from the need to practice sports protected from the severe weather, with long seasons of rain, cold and snow, as was the origin of basketball. This sport had its origins in Springfield, Massachusetts, USA in 1891[7], as a new game to be played indoors. At present, the architecture of stadiums, sports palaces and Olympic sports halls represents a new approach to the activities that takes place in them. Firstly, to carry out a sports activity or sports competition as athletes or players, and secondly, to watch an event as spectators or remote audience by TV retransmissions. The sport has become more and more complex recently. In the same way, the sports buildings have been also transformed into complex leisure centres where multi-activities and events take place (Sheard 2001).

Moreover, four different generations of sports stadiums can be established according to the year of construction and level of comfort and the services offered to the spectators: 1st generation, 2nd generation, 3rd generation, and 4th generation (Sheard 2001).

This section will provide the main architectural features of the sports halls in general, and in particular, the multipurpose sport halls and Olympic buildings in Catalonia.

Environmental comfort in sports halls

The stadiums and arenas are large areas of fields for the practice of some sports, such as football, that are organized around a central uncovered space, and in some cases, sunshades and roof protections are available only in the spaces intended for the stands and boxes. These fields are naturally illuminated in daytime, and even in this case the control of natural light may require a detailed study of visual comfort, to avoid direct or indirect glare. This shows that even in open spaces, the visual comfort, in this case of the spectators, is an additional architectural determinant, at the time of design.

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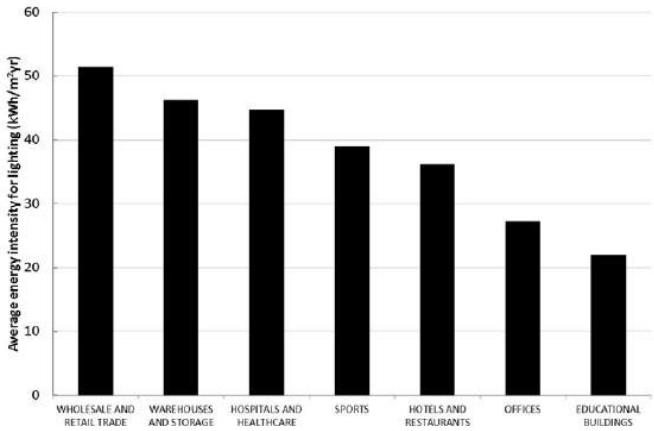
[6] Master Plan for Sports Facilities and Equipment in Catalonia, Pla director d'instal·lacions i equipaments esportius de Catalunya- PIEC, (Generalitat de Catalunya 2005a)

[7] Reglas Oficiales de Baloncesto 2008. Federación Española de Baloncesto [Online]. Available at: http://es.wikipedia.org/wiki/Baloncesto

Figure 2-30. Images of the roman amphitheatre El Djem (285 AD), in Tunisia, with 35.000 spectators' capacity.



1. WHOLESALE AND RETAIL TRADE (51 kWh/m^{2}yr)
2. WAREHOUSES AND STORAGE (46 kWh/m^{2}yr)
3. HOSPITALS AND HEALTHCARE (45 kWh/m^{2}yr)
4. SPORTS (39 kWh/m^{2}yr)
5. HOTELS AND RESTAURANTS (36 kWh/m^{2}yr)
6. OFFICES (27 kWh/m^{2}yr)
7. EDUCATIONAL BUILDINGS (22 kWh/m^{2}yr)

Figure 2-31. Column chart and ranking with average energy intensity (kWh/m^{2}yr) for lighting for building type, in non-residential building stock in Europe, North America and China (Source: Dubois et al., 2016b, pp-74).

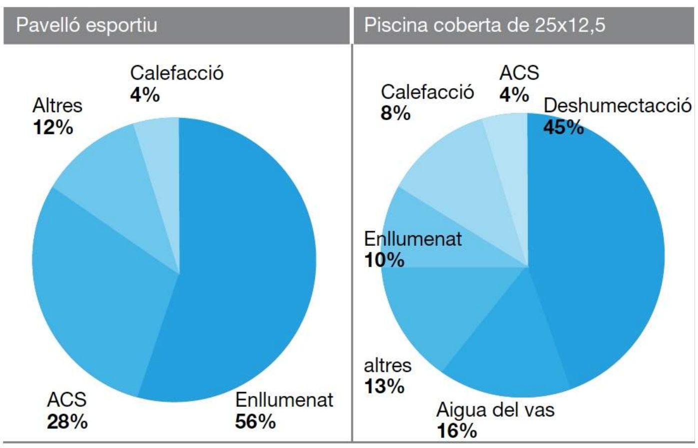


Figure 2-32. Pie chart with primary energy distribution in Catalonia for sports facilities types: indoor pavilions, left, indoor swimming pools, right (Source: ICAEN, 2012, pp. 19).

The primary energy distribution in indoor pavilions (Pavelló esportiu) in Catalonia is: 56% Lighting- Enllumenat, 28% DHW- ACS, 12% Others-Altres and 4% Heating- Calefacció.

Likewise, the physio-sports activity practice in indoor sport spaces requires a good level of quality and environmental comfort to perform different sports activities, taking into account the users' comfort needs. Among other requirements, sport halls must also be durable and require a low energy consumption (Generalitat de Catalunya 2005).

Lighting energy consumption

The results of the analysis of the non-residential building stock, from some countries in Europe, North America and China from which data is available (Dubois et al. 2016b, pp. 74), shows that the sports buildings are in fourth place, in terms of energy intensity for lighting, with an average value of 39 kWh/m^{2}yr, followed by hotels and restaurants, offices and educational buildings, see Figure 2-31. Also, this building type has high energy intensity (higher than offices and education buildings (Dubois et al. 2016b, pp. 76).

Furthermore, at regional level in Catalonia, the primary energy distribution for the multipurpose sports facility type shows that the highest demand of primary energy is for lighting with 56% of the total, followed by 28% for domestic hot water-DHW, 12% others, and 4% heating, see Figure 2-32.

Olympic Games: an opportunity to see and to be seen

In ancient times, life in the cities revolved around these mega-centres of entertainment and leisure, as in the most populated cities of the Roman Empire, to attract more and more people who wanted to live in them, see Figure 2-30. This trend seems to be as current as 2,000 years ago. In recent years[8], an important change has been experienced in this sense. The stadiums have recovered their status in the last decades, and more sports venues are being built than ever before for the Olympics Games and International sports competitions.

Nowadays, the Olympic Games are moments of splendour for the organizing cities and countries. Also, the inauguration of the Olympic Games has become a key act of the modern Olympic Games. Here it is impossible to distinguish the boundary between a world sporting event and a universal spectacle. Likewise, the Olympic Games give a global prestige to the country and to the cities that are home to them.

Olympic sports halls as a showcase

The organizers of sporting events recognize that a well-designed stadium could be a good letter of presentation for a region, city or the beginning of an urban and rehabilitation project (Sheard 2001). This intention and opportunity to extend best practices in Olympic sports halls can be exhibited through a "showcase" and it is considered positive by the United Nations Environmental Program-UNEP. For example, the London 2012 proposal was based on a sustainable program that wanted to minimize the emission of greenhouse gases and waste, among others.

[8] Detail Nº 4: Cubiertas 2004, Spanish Edition. Editorial note: Estadios deportivos como símbolos de cultura arquitectónica.

2.3.2 Users of sports halls

The observer or user interacts with the environment, in outdoors and indoors spaces. The reflection of the light in several surfaces and objects of the environment, gives the visual information to the observer. Moreover, as a consequence of that, the luminous environment can be dynamic or static, depending on the observer's position into space, the observer's views and the performed activities, the light and physical features of the space.

For the design of the sports halls, it is necessary to take into account the needs of the different people involved in the use and operation of these buildings. Some authors make a division into three groups (Sheard 2001), even granting an order of priorities: the spectators and TV broadcasts, the owners and operators, and the players or athletes. According to that, the main group is the spectators and remote audience by TV broadcasting.

However, for the visual comfort assessment during the daytime, three distinctive users are taken into account based on the requirements for sports facilities in Catalunya, where will be held a high level of competitions (Generalitat de Catalunya 2005, pp.165):

- Athletes
- Spectators
- Remote viewers and television broadcasts conditions, since TV cameras adopt different positions than spectators

Furthermore, training and competitions are established according to the level of play or activity performed: local, regional, national and international. In addition, these activities have different visual comfort requirements, see sections 2.3.3 and 2.3.4.

Athletes

The athletes or players group in further references in this work as "athlete user" is composed of three sub-groups, according to the PIEC (Generalitat de Catalunya 2005a, pp. 161), who practice sports in the multipurpose sport centres: school, elite athletes and general public.

The school group includes the pupils from the primary schools: 6 to 11 years old, the secondary schools: 12 to 15 years old, and the A levels: 16 and 17 years old, who practice physical education as a mandatory activity, included in the educational curriculum during the school schedule.

The elite athletes comprise the federated sportsmen and sportswomen, and those athletes of school age that participate in competitions outside the school activities.

The general public group includes all the players not included in the two previous sub-groups, including schoolkids outside the school schedule, non-federated athletes and general public, with occasional and/or regular sport activities practice.

The minimum visual requirements of athletes for lighting are: good recognition of objects, players, and colours, lighting uniformity in the field of play (above 1,00 m), control of glare and veiling reflections. Also, in ballgames it is important to effectively track objects in space, which depends on the size and velocity of the ball.

Spectators

The audience or public that attend a sporting event are, in further references in this work, the "spectator user".

The importance of the spectators' experience has been highlighted (Sheard 2001) emphasizing their comfort, safety and well-being from the access to the facilities, the main entrance door, the public areas, as the circulations, services and shops, until reaching the seats.

Based on that, the spectators will have an interest or not in repeating the experience.

With regard to the spectators' visual needs, it is necessary to have a vision free of obstacles in the area of stands and seats and allowing spectators:

- To be not too far from the playing area or court, where the action takes place
- The vision through the spectators located further
- The vision and the follow-up on the action in the play area, free of obstructions of the building such as pillars, ceilings, interior walls, barriers, fences, for example.

Remote audience and television – TV broadcasting

Nowadays, sports can captivate remote spectators, such as whole cities, countries and, for certain events, the whole world. This is possible thanks to television broadcasts. The sports hall spaces create the "scene" where these events are experienced (Sheard 2001) and the use of cameras of television-CTV for broadcasting has precise requirements, in further references as the "TV broadcasting". Furthermore, the sports palaces and stadiums have specific areas and complementary facilities for television broadcasts, where national or international competitions have been held or are still celebrating regularly, for example: the Olympic Games and World Cups.

There are also spaces permanently or temporarily assigned to TV cameras and commentators, which also require making shots in different positions. This must be taken into account in order not to obstruct the spectators' views. Therefore, the media companies are consulted at the initial stages of the design. As well, some designers take into account in the building design the provision of excellent television images, in terms of exposure, contrast and depth of field (Sheard 2001).

To achieve that, this author proposes to take into account in the building design the following considerations:

- Enough lighting levels in strategic locations, with the aim to improve the quality of images, such as around players, where close-ups and interviews are required
- The use of translucent roofs, to avoid shadows in the playing area
- The best possible lighting in the visual field by meeting the requirements of levels of illuminance and colour reproduction for television broadcasts
- Concentrate the spectators, when this is possible, in the areas of general television shots, to avoid images with empty seats

Vision requirements in sports

Authors agree that it is relevant to distinguish sight from vision in sports (Loran and McEwen, 1995).

Sight is the eye's ability to resolve detail and to see clearly, while vision is the interpretation of that which is seen. Sherman (1990) (cited in Loran and McEwen 1995, Chapter 1) isolates the elements involved in the process of vision that utilizes: the eyes for input from sight, the brain to integrate that information with other senses, and the body to produce an output or a response.

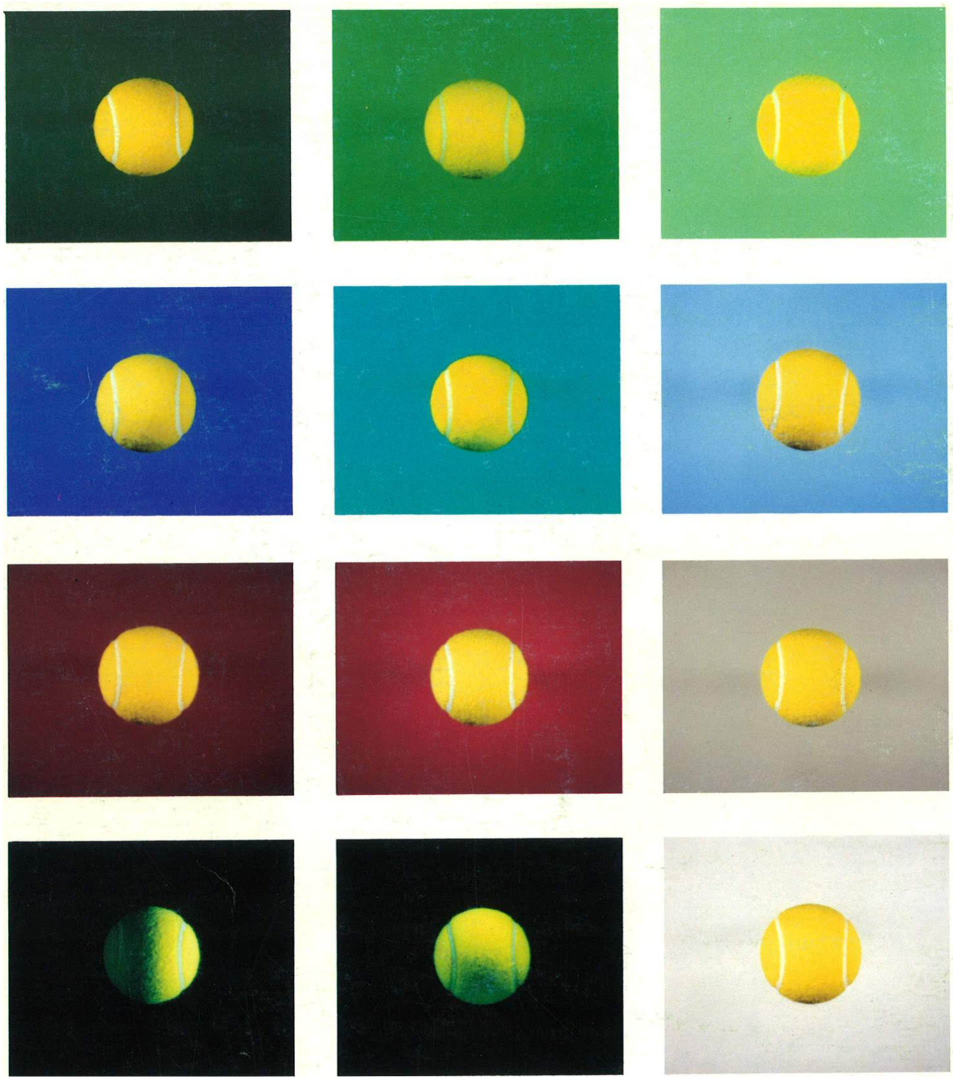


Figure 2-33. Image of a yellow ball contrasting with different colours of the background and direction of the light. (Source: IES, 1989, back cover)

Figure 2-34. Images of the Palau d'Esport de Granollers- PEG, showing different positions of users, view directions and backgrounds in a multisport hall.

The users' field of view - FOV is constantly changing since users varies their point of view and view directions, as well, the luminous environment and proportion of interior elements seen by users: spectators and remote spectators from the seating area, left and right, and athletes from the centre of the court, centre.

In sports, vision depends on the previous experience in order for the athlete to gather, analyse, process, store, retrieve, and response to the stimulus very quickly, in milliseconds.

Likewise, there are theoretical profiles of the visual skills involved in different sports, where there are more or less important (Loran and McEwen 1995, Chapter 2). For example, among others can be mentioned: the visual skills such as static visual acuity, dynamic visual acuity, ocular-motor skills, eye-hand coordination, depth perception, central peripheral awareness, visual reaction time. According to that, the sports can be classified according to the vision skills' demands, for example, for static visual acuity- SVA or dynamic visual acuity- DVA. In the case of DVA, it is defined as a measure of sensitivity to visual details when there is relative movement between the target and the observer. The athletes have to perform judgements of speed, direction and distance of objects and opponents in movement. For example, baseball, cricket and tennis has high demand in this visual skill, while basketball and football has a medium (Loran and McEwen 1995).

2.3.3 Lighting design for sports halls

With the aim of the reference of the most significant factors to achieve a good level of lighting in sports halls, lighting recommendation practices and design guides were analysed, taking into account the user requirements (Association Française de L'Eclairage- AFE 1992; Generalitat de Catalunya 2005a; The Chartered Institution of Building Engineers – CIBSE 1990; Illuminating Engineering Society of North America - IES 1989; Sports Scotland 2002; Sport England - SE 2012).

The objective of lighting for sports, including natural and artificial light, is providing a suitable luminous environment in the playing area by controlling the brightness and contrast of the playing target. Moreover, the target has to appear clear and sharp to the players, spectators and television viewers (IES 1989). Furthermore, it establishes the importance of both the quantity of illumination and the quality of illumination.

The requirements for sports lighting (AFE 1992; IESNA 1989) are related with the size of the target, for example the ball for athletes, the level of activity, visual comfort of spectators and the television broadcasting requirements, such as the position of TV cameras. In this sense, the lighting levels are related to:

- Speed of the sports
- Purpose of play
- Skill level of players
- Spectator's capacity
- Television broadcasting

To conclude, the general recommendations (CIBSE 1990; SE 2012), establish that the key points for a good illumination in sport spaces are:

- The level of illumination in the full volume of the playing area, to create equal playing conditions for all players
- The correct distribution of light, illuminance and luminance uniformity, because the fluctuation can create difficulties in judging the speed and trajectory of the playing object
- The adequate control of glare, or glare minimization

Recommendations for interior surfaces in sports halls: reflectance, finishes and colour

The reflectance - r, is the ratio of the reflected light compared to the incident light (Ruck et al., 2000, pp. 8-5) and can be expressed in percentage % or factor from 0 to 1. In terms of light, it is a characteristic of the material and indicates how much light, hitting a surface, will be reflected back (Jacobs 2003; 2004). The light and white colours have high reflectance values, up to r=0,99 or 99%, reflecting back most of the light received. The contrary, dark and black colours, have low reflectance values, due to high absorption of light against received. As well, reflectance depends on the finishing properties of the material.

High reflectance of ceiling, walls and floors decreases the utilization of light power. However, they can cause glare and poor contrast (IESNA 1989).

In general, the principal elements should be: light coloured walls and ceilings, and dark floors. The recommended values for light reflectance (CIBSE 1990) for interior elements are the following:

- Walls: r= 0,30 to 0,60 or 30% to 60%, 40-50% (Sports England, 2012)
- Back walls or screens: r= 0,20 or 20%
- Floors: r= 0,20 to 0,40 or 20% to 40%

The interior finishing has to avoid glossy surfaces and specular reflections. Instead, the surfaces have to be with diffusing and matt finishing. Walls and ceilings should be matt and not have strong patterns (CIBSE 1990).

In general, light colours of ceiling, walls and floors are recommended because they decrease the utilization of light power (IESNA 1989). However, it can cause glare. Contrary, too dark colours can cause a physiological sensation of gloomy or dark ambiance.

Specially, in particular sports with moving objects, such as a white coloured ball, considerations should be given in selecting colours. So, contrast and colour of the ball must be taking into account, because they contrast with their background in brightness, colour or both, see Figure 2-33.

The more marked the contrast, in general, the more clearly objects are perceived. As well, wall colours should be consistent and, it is preferable, to run full height, as horizontal changes could cause visual obstruction to players. Likewise, the wall colour should contrast with the floor (SE 2012).

Minimum lighting levels

Different lighting levels are required according to the sport and level of play or activity. There are established levels for artificial lighting (UNE-EN 12193:2020) for the principal area or the total area of the field of play. For training purpose, including community and non-formal competitive use, a minimum level of 200 lux to 300 lux is established. The local and regional competitions, including clubs, district and county, league competitions, require E_h 300 to 500 lux, reaching very high illuminance level in national, international competitions and TV broadcasting, from 500 to 1.500 - 2.000 lux.

2.3.4 Daylighting for sports halls

The use of daylight is highly recommended for indoor sports in the majority of the reference documents consulted, emphasising the importance of taking into consideration daylight in the early stages of design, for example, according to the building orientation and the evaluation of the impact of windows and skylights in the user's visual comfort (Sports Scotland 2002).

Moreover, the use of daylight within sports halls has a positive psychological effect upon participants or users and can contribute to energy savings (CIBSE 1990).

The current PIEC (Generalitat de Catalunya 2005a) establishes, among others, the mandatory requirement to naturally light indoor sports spaces. It also gives a series of recommendations to guarantee the balance between the use of daylight and the achievement of environmental objectives such as sustainability and energy savings, both in new and rehabilitation building design.

However, the sun or the sky seen through windows, skylights or reflections on glossy surfaces, can cause unacceptable levels of disability or discomfort glare, compromising the visual comfort of athletes and spectators. Furthermore, some sports have strict advice against the use of daylighting (Sports England 2012), for example: badminton, table tennis, gymnastics, and premier league sports.

2.3.5 Multi-sports halls

The multi- sports halls or indoor arenas are facilities to perform different activities, as culture, arts and leisure, also training and competitions of sports activities, for example: basketball, volleyball, badminton, five-a-side football.

The lighting design for multisport halls is complex. Because of different requirements should be taken into account (SE 2012), for example: type of sports, level of play and differing sports taking place at the same time.

Visual comfort in sports halls

In multipurpose sports halls, the visual comfort requirements, as mentioned in the previous sections, are diverse in relation to the type of sports, the level of play and the users, as athletes, spectators and remote audience or TV broadcasting. The visual comfort performing the visual task depends on many factors, as follows:

- The minimum lighting levels required for each sport: most of all defined by the visual task, affected by the speed of the tracking object
- The minimum lighting levels required for levels of practice: training and competition at regional, national or international
- The concurrence of the three users simultaneously: athlete, spectator and TV broadcasting
- The users' schedules: from early morning to night time
- The user position in the space, which defines multiple visual fields or viewpoints

2.3.6 Techniques for daylight and visual comfort monitoring, evaluation and simulation

The Post Occupancy Evaluation – POE are processes of obtaining information on a buildings' performance in use. In recent years, POE is being increasingly recognized and becoming mandatory on many public projects (BRE 2020). It can offer a valuable information about building performance in terms of energy consumption and environmental quality, occupants well-being, environmental and visual comfort, among others (Hirning et al. 2013).

According to Fontoynont 1999, physiological aspects that impact in the phenomena of visual discomfort and glare are difficult to measure with instruments such as light and luminance meters.

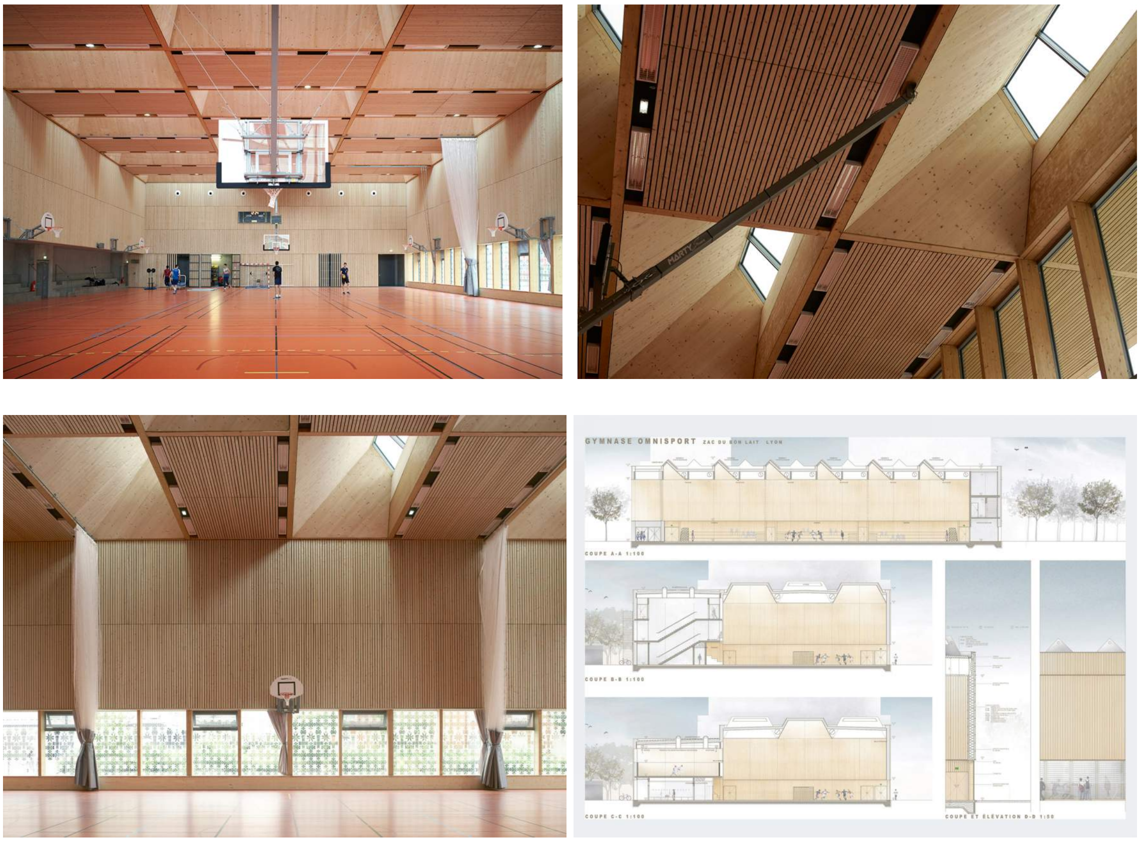


Figure 2-35. Images of sports halls with toplighting and sidelighting systems (Source: photos by ©Julien Lanoo and cross sections by Dietrich I Untertrifaller & Têkhnê Architectes.

Gymnasium Alice Milliat in Lyon (FR), (Dietrich I Untertrifaller & Têkhnê Architectes, 2014-2016)[9]: pyramidal skylights and unilateral side windows and clerestory.

Figure 2-36. Images of multi-sport hall with saw tooth roof: Pajol Sports Centre (Source:brisacgonzalez.com[10])

The Pajol Sports Centre in Paris (FR) (Brisac Gonzalez, 2012): North facing saw tooth roof.

9 https://www.dietrich.untertrifaller.com/en/projects/sporthalle-alice-milliat-lyon-fr/?filter=543

10 Available from: http://www.brisacgonzalez.com/pajol-sports-centre#:~:text=Pajol%20Sports%20Centre%20is%20a,martial%20arts%20and%20fitness%20centres.

For this reason, it is suggested to perform some luminance measurements in specific relevant directions or work planes, where visual tasks are taking place, according to the following:

- Visual task
- Visual field
- Remote surfaces

Dubois et al. 2016a, explain and compiled the protocols required for monitoring a luminous environment and to assess the performance of daylighting in existing buildings. It determines, when possible, the overall performance should be established by monitoring the light environment, before and after retrofitting the lighting and daylighting systems. Furthermore, two levels of monitoring are established as basic and comprehensive.

The comprehensive monitoring level includes measurements which should ideally to be conducted to obtain the follow metrics and procedures:

– E_h horizontal illuminance
– Daylight Factor (%)
– E_v vertical illuminance
– Photo survey
– HDR - Luminance survey

However, all the protocols and assessments are not always possible to perform, due to practical or time limitations, in real buildings or real use conditions.

E_h horizontal illuminance

The absolute illuminance values on a working plane should be taken, according to a measuring grid. The E_h measurements should be obtained several times during an entire day under a clear sky with direct sun at different times of the year (Dubois et al., 2016a), such as winter and summer solstices and equinoxes (spring and autumn) according to climate characteristics.

However, due to the variability of natural light throughout the day and year (Atif et al. 1997) measurements in situ, in clear, overcast and intermediate sky conditions, have to be complemented with numerical simulations and scale models.

Observations and photographic survey

In monitoring procedures, it is advisable to register the conditions during a significant part of the testing period, because of the very dynamic behaviour of daylight, especially under clear sky conditions. It is also preferable to take photographs during the observations, so that the evaluated lighting conditions are registered. Note observations throughout the day must be taken, such as detection of glare, sun patches, high luminance and shadows.

Luminance survey

Spot luminance should be taken of the task, according to the users, i.e.: a computer screen in offices, and compared to luminance in the immediate and remote surroundings.

The luminance spot measurements allow obtaining physical values, which the user can see in their visual field. However, performing a point-by-point luminance survey would be a high level of difficulty task, due to the difficulty of measuring and storing infinity data of points in the visual field and the passing of time introducing variations in the amount of incident light (minutes, hours).

HDR technique

The HDRI- High Dynamic Range Image technique (Inanci 2005a, 2005b) is a quick and economical solution to study temporal and spatial variations of light and obtain an approximation to the human visual range (10^{-8} to 10^{6} cd/m^2). Obtaining HDR images allows to capture the range of luminance variations in a given scene or visual field.

Since 2005, the HDRI technique was developed and consolidated as a luminance mapping tool, allowing to fulfil extensive campaigns of visual and light environment acquisition (Inanici 2010). This data can be used with calibration values, adjusting the luminance mapping to real values at key points, e.g.: maximum and minim luminance values and glare sources.

Due to the complexity of measuring the photometric properties of a luminous scene, there is need for a tool that can capture the luminances within a large field of view, in a quick manner and with high resolution. More sophisticated data analysis is possible since the whole scene can be captured (Inanici 2006; 2010).

The most common use of this technique is the evaluation of visual comfort evaluation in daylit spaces (Konis 2014; Van Den Wymelenberg and Inanici 2014; Jakubiec, Reinhart and Van Den Wymelemberg 2015). As well, it can be used in conjunction with POE surveys to assess discomfort glare (Hirning et al. 2013).

Fish eye lens

It is useful to generate hemispherical fisheye photographs that form the view of the occupant (user), since the focus is mostly on the amount of light reaching the eye, from the position of the occupant in the space, Inanici 2005b. Accordingly, hemispherical fisheye projections cover the total human view angles, that can be as 130° vertically and 180° horizontally.

Per-pixel data analysis

One obvious application of per-pixel data is to process it with automated analysis tools in currently available lighting software. Examples include the 'luminance false colour images', 'luminance iso-contour lines', and 'glare analysis' modules, for analysing luminance distribution patterns, luminance ratios, adaptation luminance and glare assessment (Inanici 2005a; 2005b).

False colour Image

HDR lighting data cannot be displayed in absolute values and full range though conventional display devices or printed. However, in false colour images, a range of colours is assigned to a specific range of luminances or illuminances values, showing the dynamic range and spatial luminance variations within a specific scene or space (Inanici 2005b).

Users' visual comfort surveys

The user interviews are useful to establish the level of visual comfort. The interviewee should be open to express himself/herself freely and spontaneously. The questions and answers should cover the following subjects such as: daylight conditions, glare, room appraisal, electric lighting and lighting control system, windows and shading devices, view out (Villa and Labayrade 2011; 2012; Dubois 2016a).

Simulations

Simulation is a technique widely used in research in general, since it allows to study and analyse complex real systems. It allows to evaluate different alternatives and different scenarios, by virtual or real scale models. It is very useful, particularly in architecture, specifically for daylight and artificial light studies.

In the same way, energy simulation for example has been expanded and advanced in buildings in recent years, in order to acquire results in terms of building performance and indoor environmental conditions.

Numerical simulation

Virtual models are made in order to determine optimal solutions within an optimization process, assisting the decision-making process and to verify different options. For example:

- to provide results in short time (that in reality would take months or years) by different models (depending on the complexity of the model)
- to optimize or improve solutions, based on results, providing a justification
- to incorporate large number of variables (size, materials, shapes, etc.)
- to analyse how the variables impacted the behaviour of the model
- to make the model as complex as possible (e.g.: obtaining photorealistic images instead of the real materialization because of economic cost and/or execution time)
- to obtain information and data under specific conditions (indoors environment, time, season of the year, sky conditions)
- it does not interfere with the building's operation

They also allow to extend the calendar of measurements and data collection in existing buildings, regarding the measurement campaigns, e.g: setting of measuring instruments, accessing to buildings and hours of use, reducing the quantity of people required to take multiple data.

The combination of real environment measurements with numerical simulations can be used to predict the behaviour of different design decisions or renovations in existing buildings (Torres 2004).

This technique has some limitations, but is widely used in different fields, particularly in building design. It is important to take into account: the input of data, the base and scenarios models construction, hypothesis of simulation, and if it is possible, to calibrate the base model with data obtained from the real environment.

Lighting simulation

RADIANCE Lighting Simulation and Rendering System (LBNL 2000, Ward and Shakespeare, 1997) is a suite of programs for the analysis and visualization of lighting design which offers highly accurate results. As a numerical simulation, it can generate physically-based rendering, follows the physical behaviour of light as closely as possible in an effort to "predict" what the final appearance of a design will be. Radiance uses ray tracing to follow light in the reverse direction and does not require the same discretization as radiosity techniques. This has significant advantages when the scene geometry is complex, and permits the modelling of some specular interactions between surfaces.

The primary advantage of Radiance over other lighting simulation programs and rendering tools is that there are no limitations on the geometry or the materials that may be simulated (RADSITE 2020).

Based on RADIANCE algorithms (Larson and Shakespeare 1998), computer programs and the assessment of the visual field have been developed. DESKTOP RADIANCE, EVALGLARE (Wienold, J. 1995-2015), DAYSIM (NRC ISE 2012; Reinhart and Walkenhorst 2001; Reinhart 2006) and DIVA-for-Rhino (Solemma 2011) are extensively used for static and dynamic simulations and false colour visualizations.

V-RAY (Chaosgroup 2011) has been shown to accomplish good and accurate results as a photorealistic rendering light simulation program, according with different researchers (Villa et al. 2010).

Lighting and daylighting design for sports halls studies

Sports Scotland commissioned a comprehensive study with the aim to support designers for lighting and daylight design in sports buildings (Sports Scotland, 2002) and updated in 2008. Case studies built in recent years were analysed, offering both guidance and information about the performance of different solutions adopted. Likewise, it offers lighting requirements according with the type of sports, such as minimum lighting levels, uniformity, materials reflectivity and methods for estimation of the average of DF. As well, it contains techniques and methods for modelling, simulation and to integrate artificial lighting, controls and passive systems, eg.: ventilation.

With the aim to identify the most suitable daylighting design strategies for this type of building, more recent studies in sports halls in Norway and Netherlands were carried out. Real buildings or case studies were analysed around the world with toplighting systems (Ding 2017; Veugelers 2017; 2018). Simulation techniques were also carried out for daylight optimization in sports halls by saw tooth roof and skylight roof. Different parameters were evaluated on annual daylight distribution base, including luminance distribution and contrast ratio, considering the interior architectonic surfaces and visual comfort (Ding 2017). Physical models and HDR images were also used for glare calculations by computer software.

2.4 Chapter conclusions

Daylight

One of the most important characteristics of daylight is its dynamics, in terms of quantity, full spectrum and colour rendering. The major benefits of natural light for humans are the visual photo-reception and non-visual effects.

The building and urban design could modify the way that daylight interacts with users, through the physical environment: openings, shape and material properties of exterior and interior surfaces.

Daylight in buildings

A minimum quantity of light is required to fully stimulate the human visual system, to be able to perceive shape, depth, distance, movement and colour, among others. Illuminance, lighting levels and their distribution on the work plane are considered to be influential to perform a specific visual task.

Light and daylight metrics

There are qualitative and quantitative metrics to describe daylight, most of all derived from artificial lighting and for horizontal work planes. However, no minimums are yet agreed for daylighting in buildings, with the exception of daylight factor DF%.

Furthermore, to achieve a good lighting depends on many factors, not just a matter of quantities, including physical and psychological factors linked to the user interaction with the luminous space.

Monitoring, measurements and simulation techniques

Metrics, protocols and procedures for monitoring daylighting in buildings which have become standards in the last decades consider: horizontal illuminance levels, daylight factor and illuminance uniformity, luminance distribution in the visual field, glare sources, size and position in the visual field. More recently, the vertical illuminance at the eye level was introduced, which can be useful in vertical work planes and for television requirements.

As well, new dynamic metrics such as DA% and UDI% were developed and simulated with contrasted results, using RADIANCE software and others derived from it.

To predict the performance of daylight systems, simulation techniques were largely tested and developed in recent years. Both static and dynamic daylight simulations results have demonstrated to be highly accurate compared with real luminous environments.

Daylighting design strategies

The architecture defines the position, shape and size of daylight systems and indoor surfaces, which affects the visual perception, with windows, skylights, floors, ceiling, side walls, among others.

The most extended daylighting strategy for buildings is sidelighting. Toplighting is also an effective solution to naturally light deep plans and one storey spaces, such as airports, sports halls and museums. Special attention has to be taken considering daylighting design strategies according to the climate conditions where the building is located, as well as their surroundings.

Daylighting design strategies have demonstrated effectiveness for improving the luminance distribution, the minimum daylighting levels, uniformity, contrast and glare sources in the luminous space. The combination of passive and active daylighting measures has proven to be successful in terms of qualitative improvement of the overall space, especially when they are considered in the early stages of the design process.

In Mediterranean climates, with high availability of solar radiation and high proportion of clear skies, solar and glare protection devices are required to maintain visual and thermal comfort.

Visual perception

Many factors also have an impact in the visual perception, due to the subjective component. Thus, a comprehensive approach is required to collect: subjective information from users, physical quantities of light and its distribution in the space.

However, there is still no agreement in which parameters can successfully predict and evaluate the visual comfort or discomfort with natural light. Users show a higher tolerance response to glare originated by natural light than artificial light. Nonetheless, advances are made in predicting glare in office spaces, considering the vertical illuminance at the eye level by DGP index and EVALGLARE software, but for static users. In addition, they take into account the relative position of the focus of the visual task area, respect to the glare source, its intensity and the background.

Experimental tests by subjects are required to study the users' perception and their preferences, in relation to luminous environments due to the intrinsically subjective characteristics of visual perception.

- *Visual field*

Visual perception is also determined by the visual task and the diverse sensibility of the Field of view-FOV. Consequently, the target and near surroundings regions or central FOV are the most sensitive to luminous variations than peripheral or far surroundings. In other words, the central area of the visual field FOV has a greater impact in the visual comfort and perception.

In the target area and near surroundings, luminance values demonstrate to have a major impact in the visual comfort than the size of potential glare sources. Accordingly, the analysis of luminance thresholds against mean luminance values of the overall scene or backgrounds demonstrates to be useful in the assessment of the visual field.

- *User interaction within the space*

The relative position of the user in the space and in relation with the glare sources, defines their visual perception, affecting the size, position and the frequency of sight of them.

Visual comfort

The visual comfort is a subjective sensation, linked to the observer or user and it is relative to the physical luminous environment.

- *Minimum lighting levels*

A minimum quantity of light is required to fully stimulate the human visual system, to be able to perceive shape, depth, distance, movement and colour, among others. Illuminance and lighting levels and distribution on the work plane are considered to be influential to perform a specific visual task.

- *Glare*

One of the most extended metrics to qualify the visual discomfort is glare and sources of glare. Moreover, it is position and view-direction dependent within the space due to user movements and visual activity tracking objects, affecting the eye adaptation.

- *Adaptation level*

The human visual system works by adaptation to the luminosity or brightness of the scene, with a high dynamic range sensitivity. It is not led by absolute luminance values but relatives.

The luminance contrast is also an important parameter to define the visual comfort. Luminance distribution have a major impact in the visual perception than quantity.

In summary, the two glare types, the absolute and contrast glare, should be considered when evaluating glare under daylight conditions.

- *Luminance distribution*

Instead of absolute values, luminances have a significant contribution in the visual comfort according to their distribution and contrast in different sensitive areas of the field of view – FOV: the foveal and peripheral regions.

Mean luminance values of the scene or background, size, geometry and position of glare sources and luminance contrast are influential parameters to be considered in the visual field.

Accordingly, luminance values, distribution, contrast and position in the visual field - FOV should be assessed for a visual comfort.

Lighting for sports halls

The environmental conditioning of indoor multi-sport facilities requires, among others, good lighting levels and optimal visual comfort.

In general, values and parameters recommended for sports lighting varies according to the type of sport, speed of the target and common view directions of athletes. Specific requirements are also established for artificial light, according to the level of play and type of sports, including TV broadcasting conditions, in terms of quantity and quality of light. For example, 300 lux – 400 lux are the minimum horizontal illuminance levels for training and up to 1.500 lux for competitions. Minimum values for illuminance uniformity on the court, materials, colours and reflectance factors of interior surfaces are advised. Although the use of daylight is promoted in mandatory regulations, no minimum quantities are established.

Likewise, the presence of daylight can be an issue for sports competitions and TV broadcasting, due to its variability in short periods of time. Accordingly, solar protection, daylight control and total black-out devices are highly required in sports halls which host competitions and televised sports events.

Sports halls users

Three main groups of users are identified for sport facilities, with different needs linked to their visual task, position and movements over the court: athletes, spectators and TV broadcasting. Because users and their visual task are dynamic or in movement, the visual comfort assessment must consider vertical work planes.

Visual comfort in sports halls

Sports activities have different requirements of lighting levels and distribution, according to the level of play and type of sports, including the size and velocity of tracking objects.

Good quality of light is also essential to guarantee the visual comfort in terms of uniformity, balance and distribution of luminances and minimum contrast in the visual field FOV. Qualitative parameters must be considered to allow the visual system to adapt to luminous conditions, such as the absence of glare, excessive contrast and adaptation level.

Particularly in sports spaces, the study of the visual field is complex because the visual task and sports users are not static. Multiple work planes must be considered in the assessment of visual comfort, to take into account the adaptation and transition processes of the visual system to different view directions or virtual work planes (vertical and horizontal).

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3

Research methodology

Previously, the Chapter 2 described the State of the Art and the framework to conduct this thesis. This chapter describes the research methodology designed and implemented from an architectonic and holistic approach and developed in three main parts. Objective and subjective data are collected from case studies, comprising in-situ measurements, such as horizontal and vertical illuminance. As well, it includes high dynamic range images survey, glare and contrast analysis in the field of view, simulations, an experimental test and visual comfort surveys. In addition, it analyses the optimisation of daylight at the initial stages of the design development of a new sport facility in Tarragona.

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3.1 Methodology scheme

To investigate if toplighting systems could perform adequately in sports halls of Mediterranean climate, regarding the visual comfort of users, quantitative and qualitative metrics and parameters are proposed to be included in the methodology from a comprehensive and an architectonic approach.

Based on the state of the art previously discussed, the methodology is designed to collect information about both the performance of daylighting systems and the visual comfort in existing and simulated top-lit sport halls. For that, some procedures are implemented for monitoring daylight in buildings and the assessment of visual comfort, which have become standards in the last decades (Baker et al. 1993; Atif et al. 1997; Fontoynont 1999 and 2002; Ruck et al. 2000; Baker and Steemers 2002; Painter et al. 2010). Furthermore, it is supported by more recent published reviews (Wymelenberg and Inanici 2014; Torres and Lo Verso 2015; Dubois et al. 2016a). However, the assessment in sports type of building is complex because both visual tasks and athletes are dynamic. Multiple work plane, view point and view directions must be evaluated.

Moreover, there is still no agreement in which metrics or parameters can successfully predict and evaluate the visual comfort under natural lighting conditions due to the subjective perception of users, among others (Rockcastle and Andersen 2013; 2015; Pierson et al. 2018).

This research is organized in three main parts, regarding the main research question about how much can daylighting and toplighting contribute to the visual comfort in sports halls, see Figure 3-1. An array of procedures and techniques are proposed according to the following:

- 1st Part: Visual comfort in top-lit sports halls in Barcelona, see section 3.2
- 2nd Part: Assessment of daylighting design strategies to improve visual comfort in sports halls using simulations and experimental test, see section 3.3
- 3rd Part: Application of daylighting design strategies, see section 3.4

The first part of this work evaluates the performance of naturally lit and, in particular, top-lit sports halls built for the Barcelona 1992 Olympic Games. Thirteen different top-lit sport buildings in Catalunya were assessed, see points 3.2.1 and 3.2.3. It included monitoring procedures, such as horizontal and vertical Illuminance, uniformity of illuminance U, Daylight Factor, subjective perception, luminance distribution in the FOV by HDR survey, among others. These techniques were complemented with numerical simulations, due to the lack of information or due to practical limitations to perform in-situ measurements in in-use buildings, see point 3.2.2.

Then, a basic and comprehensive visual comfort assessment was carried out taking into account the athlete and spectator/remote spectator points of view, view directions and the visual field or field of view – FOV, see point 3.2.3.2. For accomplish that, a simplification of multiple view positions and view directions are proposed to be carried out the HDR survey.

After classifying the specific requirements for sport halls' users, visual comfort and discomfort situations are identified in the case studies.

In the second part and based on previous results, daylight design strategies are suggested for the improvement of visual comfort in four of the Olympic sports halls, see point 3.3.1. Daylighting design recommendations to improve visual comfort in sports halls in Catalonia were compiled and based on the visual comfort assessment.

Photorealistic and calibrated images were obtained to test and validate the design measures proposed through experimental tests, see point 3.3.2. Additionally, the panel responses were collected and analysed to obtain qualitative information about the users' visual perception and preferences in sports halls.

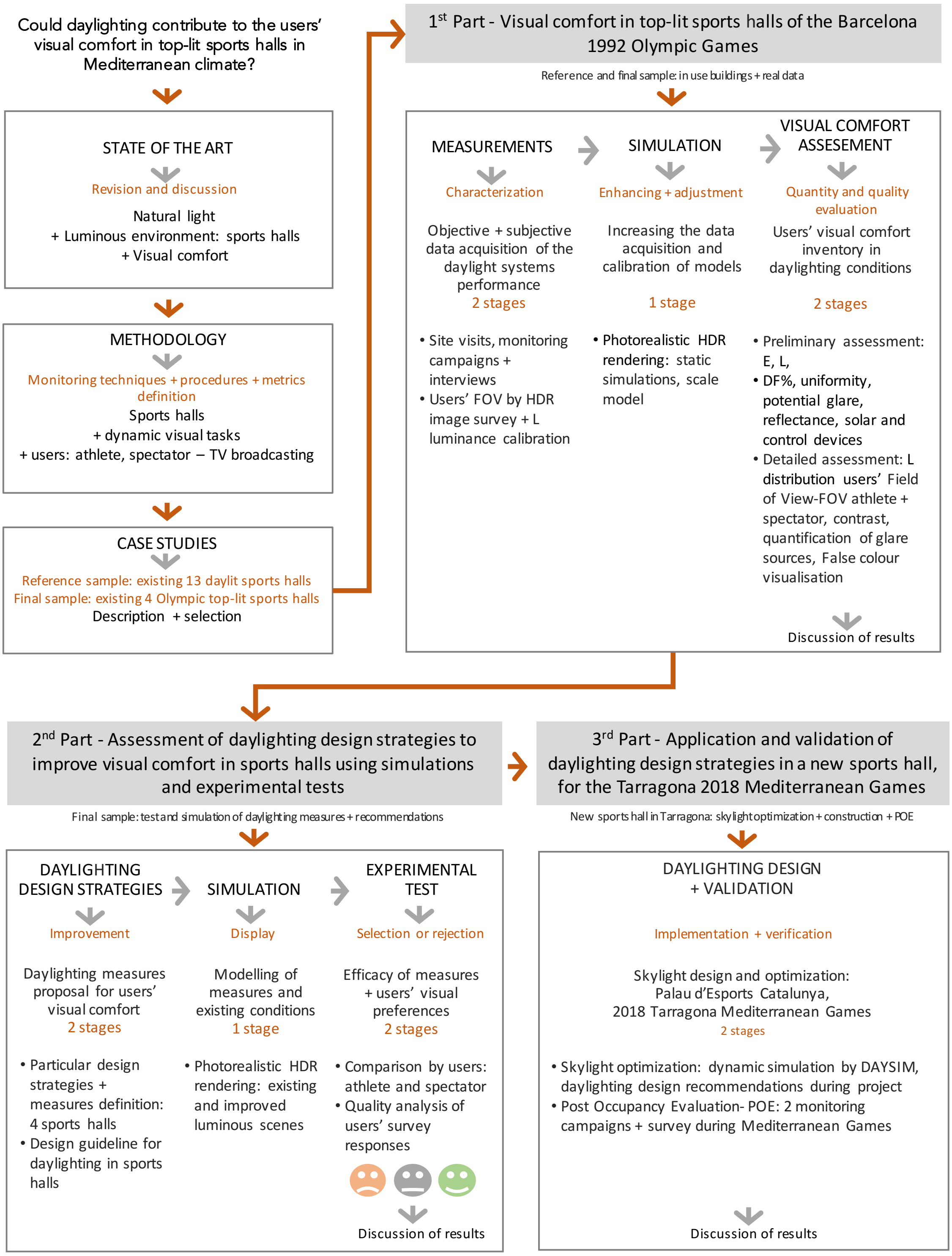


Figure 3-1. Methodology scheme proposed for this research, describing of main parts with their respective stages and procedures.

The third part was completed at the Catalonia Institute for Energy Research - IREC and presents daylighting design strategies, which are compiled for the optimisation of natural light in sports halls of Catalonia. These guidelines were implemented in the building design of the new Palau d'Esports Catalunya, built for the Tarragona 2018 Mediterranean Games. The goals of the optimisation of the central skylight by dynamic simulations are also contrasted and verified with two Post Occupancy Evaluation - POE campaigns, see points 3.4.1 and 3.4.2.

After the completion of the three main parts, objective and reference data was compiled, including quantity and quality metrics, and subjective information in real and simulated scenarios, as follows:

- Subjective data related to perceptual parameters from on-site assessments of existing sports halls by the author.
- Users' preferences and rejection criteria to choose comfortable daylit environments: as athletes and spectator/remote spectator.
- Spectator' visual comfort survey, completed during international competitions and TV broadcasting conditions.

3.1.1 Case studies

A case-study approach is adopted for the first and second parts of the research, to characterize the real performance of top-lit systems in sports halls in Mediterranean climate, see next Chapter 4 for the reference and final samples.

This approach has several advantages, as offering a real laboratory with existing and in-use buildings, and enabling to investigate frequent issues related to the visual comfort of users with this type of building. Establishing an extensive sample also allows to determine the feasibility of performing different procedures in each case study. This made possible the adjustment of the sample and finally, the design and organization of the measurements campaigns.

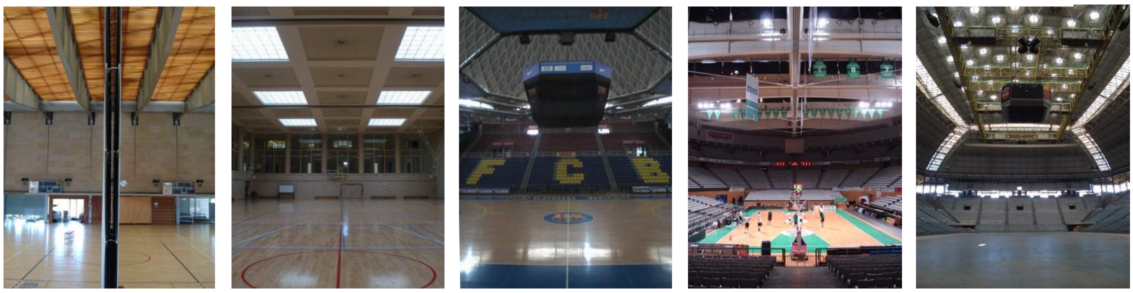
According to the Consell Català de l'Esports- CCE (Generalitat de Catalunya 2005b) sports halls type, a reference sample of thirteen multipurpose sports halls or triple pavilions - PAV- 3 was selected to carry out an initial or basic evaluation, containing Olympics and non-Olympics buildings.

Once the reference sample was established, plans, cross sections, elevations and details were collected, in order to obtain graphical and detailed information of the luminous environment and daylight systems. This information is also required for the organization of the monitoring campaigns and the graphical representation of spot measurements. Likewise, building documentation was used to build virtual and scale models to perform simulations.

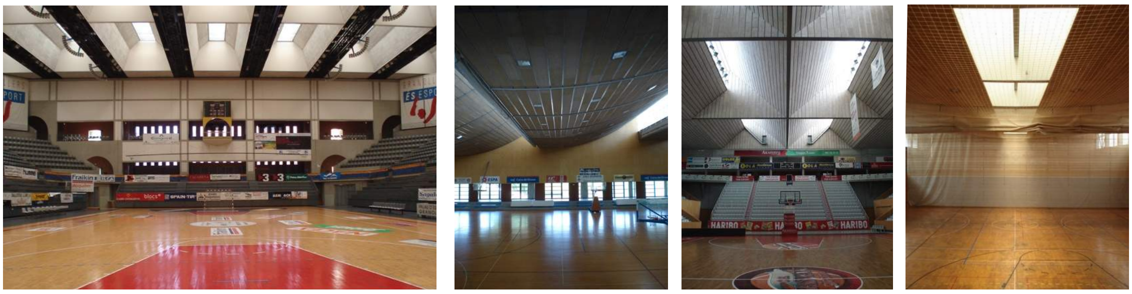
In the second part, four existing Olympic sports halls were selected for the final sample, to perform a functional and comprehensive assessment, as well as an experimental test.

The third part was developed on the basis of a new sports hall, built for the Tarragona 2018 Mediterranean Games, see Chapter 8.

Complex Esportiu Municipal L'Espanya Industrial **CEM EI**	**Complex Esportiu Municipal La Verneda** **CEM LV**	**Complex Esportiu Municipal Olímpics Vall d'Hebron** **CEM VH**	**Complex Esportiu Municipal del Raval Can Ricart** **CEM RCR**



Complex Esportiu del Consell Català de l'Esport **CE CCE**	**Institut Nacional d'Educació Física de Catalunya Montjüic** **INEFC**	**Palau Blaugrana FC Barcelona** **PBFCB**	**Palau Municipal d'Esports de Badalona** **PMEB**	**Palau Sant Jordi** **PSJ**



Palau d'Esports de Granollers **PEG**	**Pavelló Poliesportiu Municipal de Banyoles** **PPMB**	**Pavelló Municipal de Girona Fontajau** **PMGF**	**Poliesportiu Municipal Virrei Amat** **PVA**

Figure 3-2. Images of the sports halls selected for the reference and final samples.

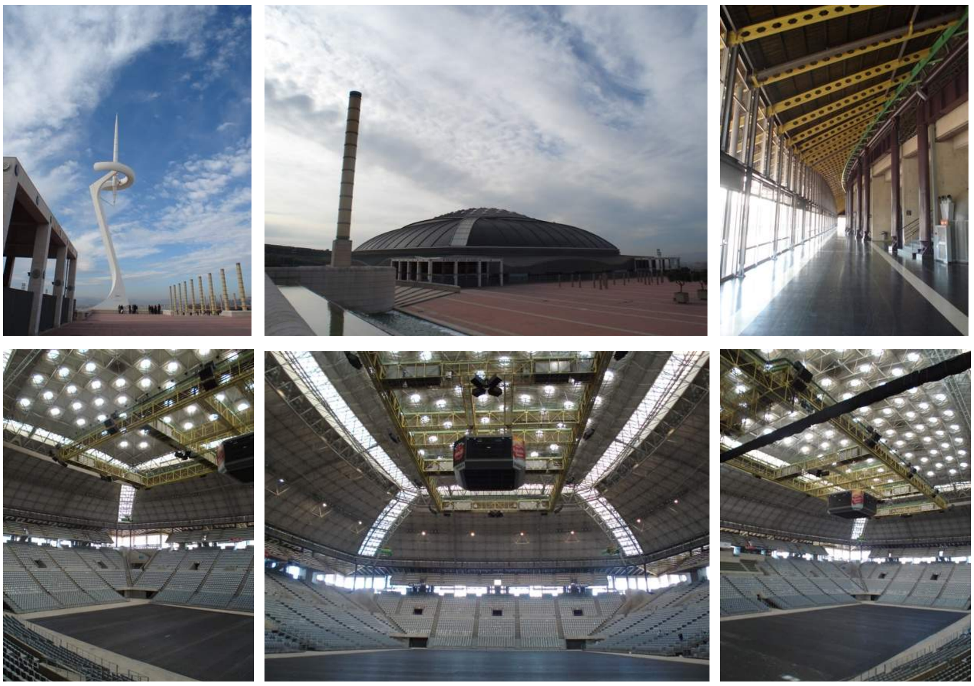


Figure 3-3. Example of photographic survey conducted in the reference sample: outdoors and indoors features of Palau St Jordi -PSJ building.

3.2 1st Part: Visual comfort in top-lit sports halls of the Barcelona 1992 Olympic Games

The aim of the first part is to assess the performance of daylight systems, collecting subjective and objective data in existing sports hall buildings in Barcelona and regarding the visual comfort requirements. Likewise, to correlate the integrated daylight design strategies with its impact on the visual comfort of users, considering overcast and clear skies. Accordingly, the procedures performed in this 1st Part, see Table 3-1, are the following:

- Measurements: 2 stages
- Simulations
- Visual comfort assessment: 2 stages

Parts and phases		Goals	Stages	Procedures and metrics	Case studies	Outputs	Year
1st Part - Visual comfort in top-lit sports halls of the Barcelona 1992 Olympic Games	MEASUREMENTS	*Collecting objective and subjective data: performance of daylight systems + visual comfort*	*1st*	Site visits- monitoring campaigns: • Photographic survey • In-situ measurements: E_h horizontal illuminance, E_v vertical illuminance at eye level, DF%, exterior E_h horizontal illuminance • Interviews • Subjective evaluation	Reference sample	Annex III: Case studies results Annex IVC: Published papers and contributions	2006-2007
			2nd	Users' field of view FOV survey + calibration: • Viewpoints definition: athletes and spectators/ remote spectators- TV broadcasting • HDRI visual field survey • Luminance spot measurements • Materials reflectance	Final sample	Annex III: Case studies results	2007-2009
	SIMULATIONS	*Increasing data + calibrating models*	*1st*	HDR rendering of real and improved conditions: • 3D virtual models • Static simulations for photorealistic rendering • Scale model: artificial sky and Heliodón	Final sample	Annex IV-B AGAUR Scholarship 2009: CIHE, FADU, UBA, Argentina	2009-2010
	VISUAL COMFORT ASSESSMENT	*Characterizing the users' visual comfort + identifying discomfort situations*	*1st*	Quantitative and qualitative visual comfort assessment: • E_h horizontal illuminance level • E_h Uniformity on the court/ playing area • Glare sources and excessive contrast	Reference sample	Diagnosis of frequent situations regarding visual comfort in top-lit sports halls	2010 + 2017
			2nd	Detailed assessment of the athlete + spectator field of view - FOV: • Potential glare sources: luminance values and distribution • Contrast, luminance ratios and subjective brightness	Final sample	Discussion of results and partial conclusions	2012-2014

Table 3-1. Methodology proposed for the first part of the research: Visual comfort in top-lit sports halls of the Barcelona 1992 Olympic Games.

Figure 3-4. Images of the exterior premises of CEM EI building, showing the exterior conditions of measurements carried out: under clear sky, left, and overcast sky conditions, right.

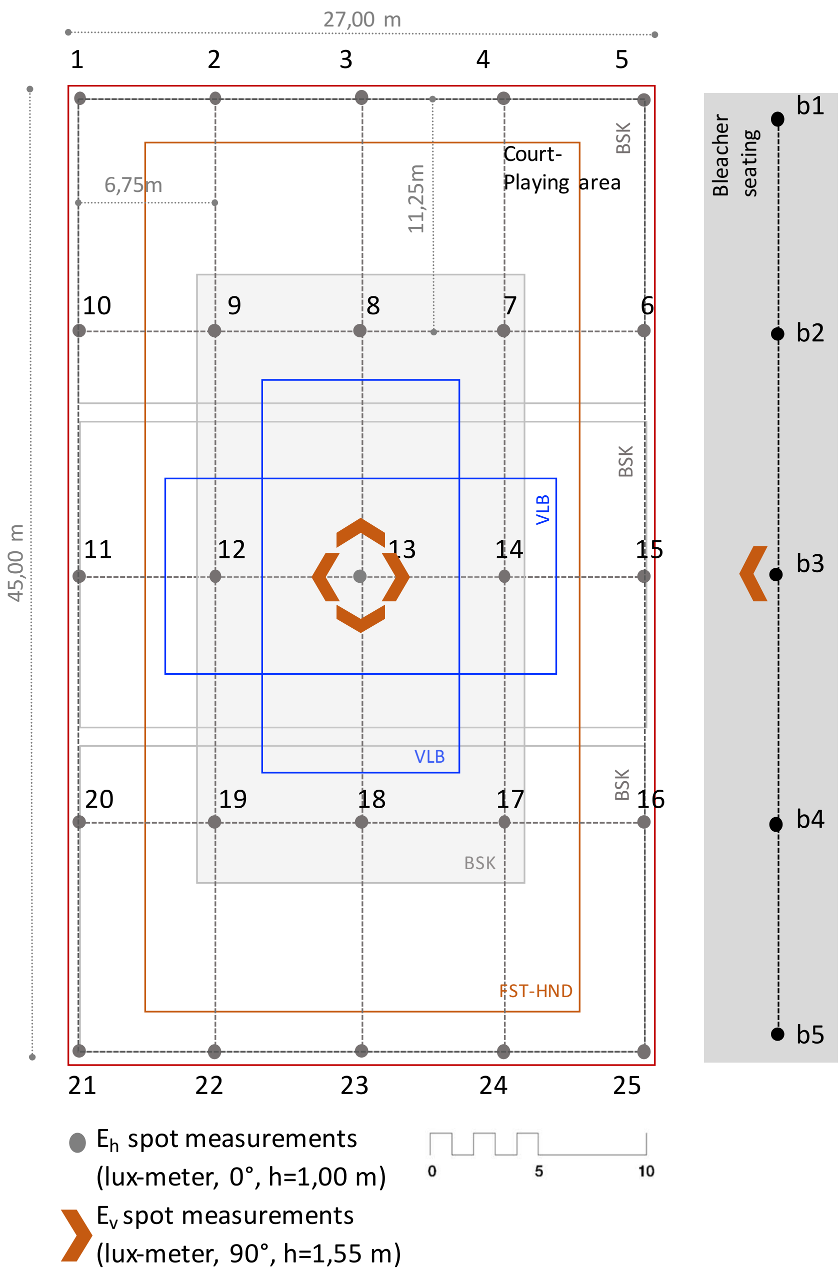


Figure 3-5. Scheme of the court layout showing the orthogonal grid with a minimum of 25 sensor's position for Eh and Ev spots measurements.

3.2.1 Measurements

Objective and subjective data was collected from existing top-lit sports halls or case studies to perform basic and comprehensive assessments of daylighting and visual comfort.

Based on the most suitable metrics to assess the visual comfort in existing and in-use buildings (Atif et al. 1997; Fontoynont 1999 and 2002; Inanici 2005a; 2005b; 2006; Dubois et al. 2016a) monitoring techniques and measurements were carried out in the court of sports halls, as follows:

- Site visits and monitoring campaigns
- Users' Field of View - FOV survey + calibration

The full text of the results and the preliminary conclusions of this phase are presented in Chapter 5, Appendix IV-B and IV-C (Gonzalez Matterson et.al. 2008).

3.2.1.1 Site visits and monitoring campaigns

One of the major advantages of site visits is to obtain a high amount of information and take first impressions of the building. Likewise, it provides a fast verification about if toplighting systems are still currently in-use and if it is possible to perform measurements in the selected case study or the contrary dismiss it, adjusting the sample. For that, site visits were conducted to collect diverse information from the sample about the daylight conditions, the luminous environment and the users for a basic and comprehensive assessment in the reference sample. The following procedures were completed in the reference sample:

- Photographic survey
- Spot measurements and reference values: weather and sky conditions, horizontal illuminance - E_h vertical illuminance - E_v and daylight factor - DF%
- Interviews with building managers and maintenance staff
- Subjective evaluation and notes: users' schedules, frequent visual discomfort issues, overall luminous scene perception, finishing elements, daylight control and solar shading devices

Photographic survey

Photographic surveys were carried out, in correspondence with site visits. Information from case studies were collected and registered during surveys, such as toplighting and sidelighting systems, solar protection devices and finishing surfaces, materials and colours, the activities performed considering the levels of play as training, competition and TV broadcasting, and if the artificial light is in use.

Spot measurements and reference values

One of the requirements to the visual comfort are minimum quantities of light in the work plane to see the objects of interest and to achieve a minimum contrast to distinguish elements and colours. Minimum levels of lighting are established for sport practice, most of all for artificial lighting, for training and competitions levels of play. The TV broadcasting competitions are the most demanding conditions for lighting, in terms of lighting levels and uniformity on the court, as well, with no glare sources and a good balance of luminances in the cameras' FOV.

Accordingly, indoors illuminance measurements for natural and artificial light were carried out in the reference sample, according to orthogonal grid, see Figure 3-5.

Measurements with luxmeter in both horizontal (0°) and vertical (90°) positions of the photocell were made (Evans et al. 1999; Córica and Pattini 2005; Dubois et al. 2016b) and the following data was collected:

- Horizontal illuminance - E_h
- Vertical illuminance- E_v
- Daylight factor- DF%
- Exterior horizontal illuminance- E_h

The horizontal illuminance E_h measurements were obtained for natural and artificial lighting conditions in the most representative areas of the court. The following areas of the court were considered for the visual comfort assessment:

- The court or playing field
- The bleachers or spectator' seating areas
- Dedicated spaces for TV cameras or television broadcasts

The data obtained from measurements is transcribed and organized in worksheets and files, see results in Appendix III.

- Horizontal illuminance levels - E_h

The measurements were carried out considering the court, seating area and user's positions and viewpoints over the space, see Figure 3-5. A minimum of 25no. points were selected in the court or playing area at ≈+1,00m above the floor, resulting in an orthogonal grid covering a surface of 45m x 27m. Also, 5no. points were measured in the central zone of the spectators seating area. A total of 10no. buildings of the reference sample were surveyed.

- Daylight factor - DF%

Daylight factor measurements were carried out with overcast sky conditions (Atif et al. 1997). Both indoor and outdoor horizontal illuminance levels E_h were obtained, according to the orthogonal grid in see Figure 3-5. A total of 5no. buildings of the reference sample were surveyed.

- Vertical illuminance- E_v

The vertical illuminance E_v measurements were carried out at eye level (≈+1,55m above the floor). The position for taking the measurements were from the centre of the playing area towards the four principal sides of the court, and from the bleachers towards the court, see Figure 3-5. A total of 10no. buildings of the reference sample were surveyed.

- Exterior horizontal illuminance- E_h

To obtain reference values of the exterior horizontal illuminance or daylight availability, measurements in a horizontal position (0°) by luxmeter were carried out, after and before the Indoor E_h survey is completed. A total of 10no. buildings of the reference sample were surveyed.

Due to the impossibility to access to the sports halls roofs, in most of the cases, the E_h exterior measurements are made in selected areas far from surrounding buildings, to minimize obstructions in the luxmeter photocell.

Interviews

An interview with the building manager and maintenance staff was conducted, once the site visit was organized.

- Management

A total of 10no. interviews were completed during the site visits from 2006 to 2008. Different questions about the use of sports halls were requested as follows:

- Type of sport halls users: general public, schools, elite athletes, TV broadcasting
- Users' timetables: use during the weekdays and weekends, year
- Frequency of sports events: amateur, regional and international competitions
- Use of artificial lighting and different levels of play: training, regional, national international competitions
- If there are HVAC systems and the frequency of use during sports: ventilation, cooling and heating
- General comments about lighting and conditioning systems

In addition, supplementary information was required with an extended questionnaire sent to the managers about the final sample, containing timetables and levels of play: training, competition, weekdays, weekends, use of artificial lighting, including electricity consumption, power, hours of use.

- TV sports events realization interviews

In order to obtain the requirements for TV broadcasting in sports competitions, an interview with TV sports producers of TV3 - Televisió de Catalunya was done. As a result, a brief of key issues related to daylighting and lighting conditions for televised sports events was completed, see Appendix III. This was useful to support the daylight design recommendations in the 2nd Part.

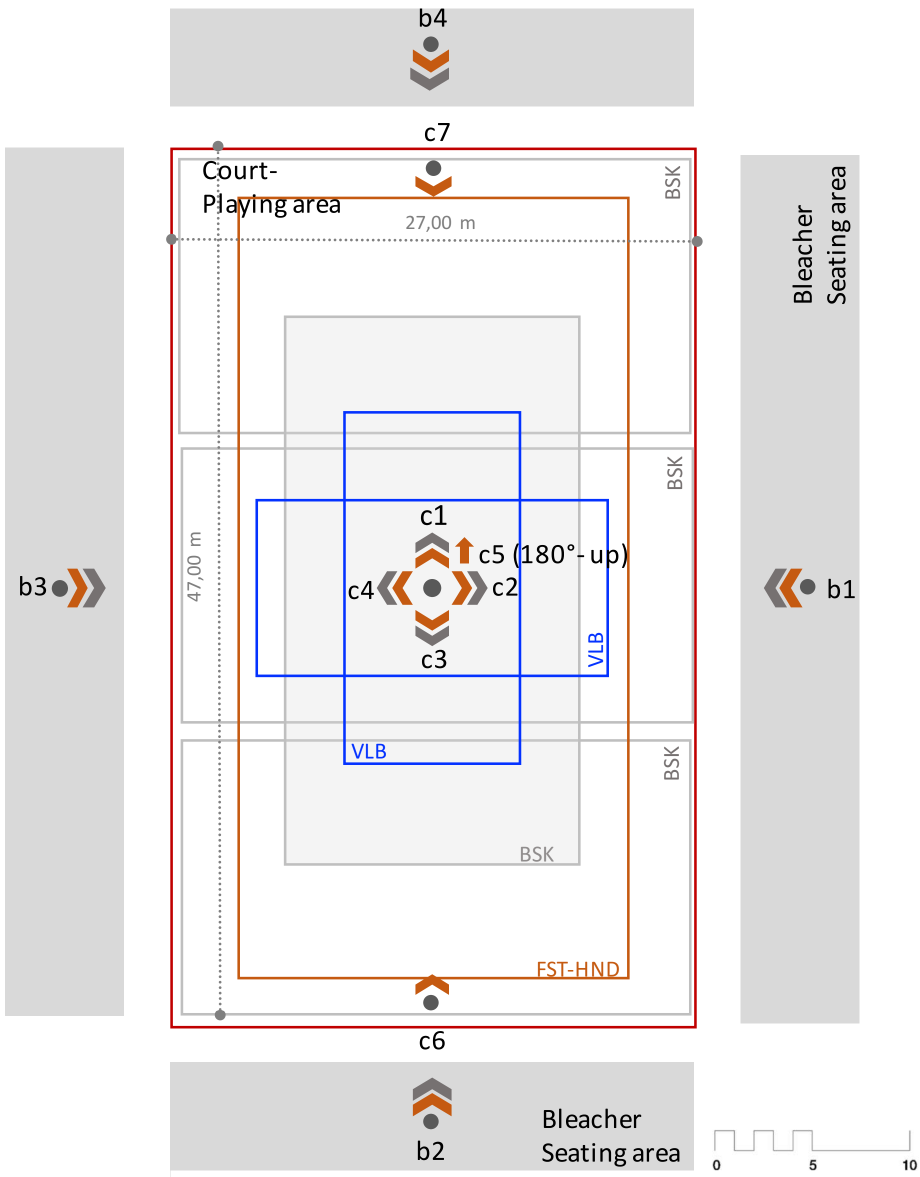
Subjective assessment

Subjective notes were taken to reflect first impressions about the overall luminous environment, glare sources and excessive contrast, user interaction with the space. The observations were complemented by the photographic survey. As well, the finishing elements and the visual perception were registered.

Accordingly, the case studies were evaluated according to the next:

- Glare sources - Gs
- Shading and daylight control devices
- Contrast and adaptation level
- Users interaction with the luminous environment
- Luminous environment: overall perception

This subjective evaluation was useful to identify, in a very preliminary stage, certain frequent issues related to the users' visual comfort. For example, low illuminance level, sun patches in the playing and seating area, glare and excessive luminance contrast, which were recognizable but not quantifiable.



● View points for equipment position (h=1,55)

View direction for HDRI acquisition (digital camera + fish eye 180°)

$L_{uminance}$ spot measurements (luminance-meter, 1°)

Figure 3-6. In situ measurements for users' field of view – FOV survey and calibration: court layout scheme showing HDR acquisition viewpoints and luminance (L) spots measurements carried out in the final sample.

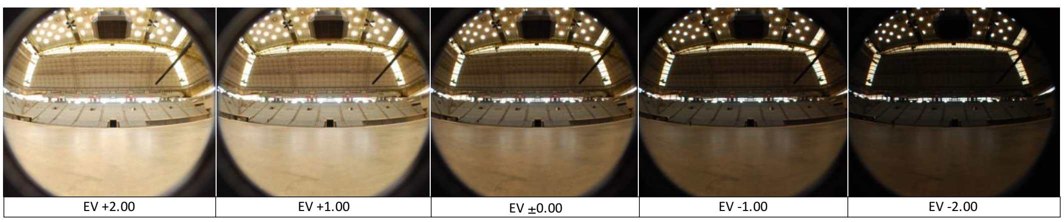


Figure 3-7. LDR images taken with different EV values: from EV +2.00, left, to EV-2.00, right.

In addition, this evaluation supported the selection of methods and simulation tools used in the 2nd stage of measurements, in particular, for the study of luminances in the user's visual field and in training and competition activities, including television broadcasting.

3.2.1.2 Users' Field of View - FOV survey and calibration

In order to perform a comprehensive visual assessment of the luminous environment, analysing the distribution of luminances and quantifying potential glare sources in the users' field of view – FOV (CIE 112:1994; CIE 169:2005), the following procedures were proposed:

- Viewpoints and view directions definition
- High Dynamic Range Image- HDRI survey (Inanici 2005a and 2006): athlete and spectator/TV broadcasting FOV
- High Dynamic Range Image - HDRI calibration: with luminance L reference values by PHOTOSPHERE software (Ward 2014, Version 1.8.16U)
- Material reflectance survey (Evans et al. 1999, Dubois et al. 2016a)

The viewpoints and view direction were defined to simplify what users commonly see during the visual task in sports activities.

The High Dynamic Range - HDR technique allows the acquisition of luminance maps with a detailed survey of luminances in the visual field and in a very short period of time (Inanici 2005b, Dubois et al. 2016b). For that, HDR images were obtained for each view direction in the final sample, capturing and registering the simplified virtual work planes or the users' FOV (Inanici 2005a and 2006; Torres 2004; Jacobs 2007). In addition, a post-processing adjustment for calibration was performed (Jaloxa 2012) and subsequent analysis with PHOTOSPHERE software (Ward 2014, Version 1.8.16U) to convert each pixel in brightness values for False Colour Analysis.

Viewpoints and view directions definition

To register and capture in one HDR image what each user commonly sees during the performance of the dynamic visual task in users' visual field during the sports activities, virtual vertical and horizontal work planes were established (CIE 112:1994; CIE 169:2005). For that purpose, simplified viewpoints or user's specific position in the space towards main directions or view direction for the athletes and the spectators/TV broadcastings were defined.

- Athlete field of view - FOV

Five view directions were selected representing athletes' visual fields. The Figure 3-6 shows the view point definition considering the user standing in the centre of the playing area or court or view point, looking towards five 5 virtual work plane directions: 4 vertical planes C1, C2, C3, C4, comprising both lateral, front and back, and 1 horizontal C5, looking at the ceiling or up, see Figure 3-9.

- Spectators, remote spectators and TV broadcasting field of view - FOV

To establish the spectators and remote spectators' visual fields, the user is considered seated in the central area of spectator seating area or bleachers b1, and from the spaces dedicated to the television cameras for broadcasting.

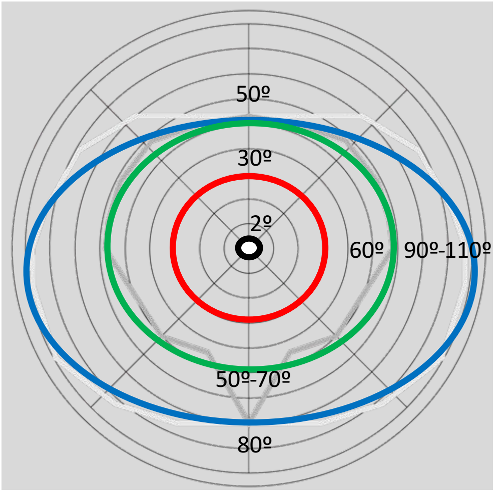


Figure 3-8. Graphic representing areas of in the visual field or FOV selected for the analysis of user's viewpoints.

User field of view- FOV areas of interest: focus 2° in white, near surrounding 30°, intermediate 60°, far and background 90° (based on Inanici 2005b, pp.25, 26)

Figure 3-9. HDR images with fish eye representing users' viewpoints: athletes C1, C2, C3, C4 and C5, and spectator B1.

Figure 3-10. HDR images with fish eye representing spectators and TV viewpoints.

B2, left, B1, centre, and B1 with blinds partially shutter down, right.

In general, the same viewpoint that is selected for spectators is selected for TV camera. From one up to three view directions from this location were considered towards the virtual vertical work plane in the centre of the court or playing area. In some cases, more than one viewpoint was established, as b2, b3, b4, taking into account: lateral openings, blinds, and court division, that could affect the users' perception of the luminous environment, see Figure 3-10.

High Dynamic Range Image - HDRI visual field survey

The HDR technique has been incorporated into this work because it allows an exhaustive survey of luminances in the visual field in a very short period of time. The image obtained describes the photometric characteristics of the scene with more accurate sensibility than the human eye perception. In addition, this technique offers a reliable luminance map (Inanici 2005b; Dubois et al. 2016b) with a post-processing tools for calibration (Jaloxa 2012) and subsequent analysis with computer software to convert each pixel in brightness values, as a False Colour Analysis and potential glare source detection.

In order to assess the distribution and the values of luminances in digital images, the HDR survey was carried out with a reflex digital photographic camera from the viewpoints and towards the view directions established. For that, a sequence of 5no. Low Dynamic Range- LDR images with multiple exposure values- EV were obtained for each view direction, capturing the virtual work plane and the users visual field (Inanici 2005a; Jacobs 2007), see Figure 3-7.

With the aim to perform the FOV survey by HDR technique, a photographic fisheye lens converter, covering 180° vertically and horizontally, was used to obtain complete images of the visual field of users in a single photographic shot (Inanici 2005b), see Figure 3-9 and Figure 3-10.

After that, the LDR images were combined into one HDR image or luminance map by PHOTOSPHERE software (Ward 2014, Version 1.8.16U) and stored in *.hdr format, see Figure 3-11. This program uses a self-calibration algorithm (Ward 2014) based on the response curve of the camera, which is established on the sequences of shots with multiple exposures (Torres 2004; Inanici 2005a).

A minimum of 3no. and up to 6no. HDR surveys were conducted in each case study of the final sample, see Appendix III for complete results.

Luminance spot measurements

In order to calibrate HDR images (Torres 2004; Inanici 2005a; Jaloxa 2012), in-situ luminance measurements with luminance-meter were obtained at specific points in the visual field. At the same time, the HDR survey was carried out. The images were obtained considering the user's viewpoints established in the previous point, according to the camera settings.

A total of 7no. luminance surveys was carried out in four 4 case studies of the final sample, see Appendix III.

Different spots and surfaces were selected in the scene as reference points, e.g.: as the centre of the playing field on the floor and daylight openings. In most of cases the maximum L values were also obtained to have absolute values of potential glare sources.

Figure 3-11. HDR images of INEFC building obtained in-situ and after calibration.

INEFC L luminance sport measurements in cd/m^2, left, and resulting calibrated image by PHOTOSPHERE, right.

INEFC (05/11/2009, clear sky) C1: 3:01 PM (red dots= luminance values from in-situ measurements)

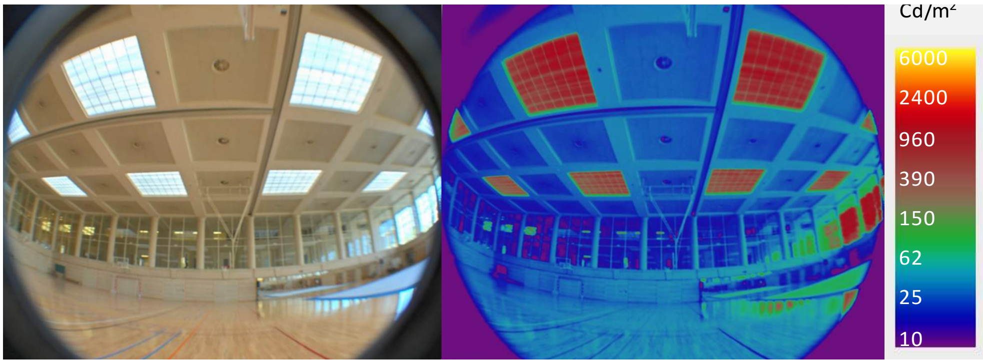


Figure 3-12. HDR images of INEFC building after calibration, left, and False Colour Analysis, right.

Calibrated HDR image by PHOTOSPHERE software.

INEFC (05/11/2009, clear sky) C1: 3:01 PM

Figure 3-13. Evaluation of the Visual Field of View –FOV: HDR image from athlete viewpoint.

INEFC L luminance sport measurements in cd/m^2 (red dots) and resulting calibrated values by PHOTOSPHERE software (white and black dots).

INEFC (05/11/2009, clear sky) C1: 3:03 PM

In order to avoid reading errors in the luminance meter, a minimum of three measurements were taken for each reference point. In addition, notes were made registering where the point and values of 3no. readings are located. Afterwards, the data was recorded in a worksheet file and the mean luminance values of the three readings were extracted. This data was presented in the images of each building, identifying which HDR image corresponds to each group of measurements, see Figure 3-11.

- High Dynamic Range - HDR images calibration

HDR images obtained were calibrated by PHOTOSPHERE software (Ward 2014, Version 1.8.16U) in order to have absolute validity. The brightness value of each pixel of the luminance map was adjusted with in-situ luminance reference values obtained. These values were obtained in the same session of the HDR survey with luminance meter, see Figure 3-11. A post-processing adjustment for calibration (Jaloxa 2012) and subsequent analysis was carried out with PHOTOSPHERE software to convert each pixel in brightness values for False colour visualization.

The calibration factor - CF (Jaloxa 2012) for the response curve of the camera Nikon D60 was established after several trials with the luminance values obtained at a few points of the scene from the case studies of the final sample, according to the following:

$$CF = Luminance_{Real}/Luminance_{HDR}$$

Equation 3-1. Calibration factor

Where: L_{real}: real luminance obtained by luminance meter (cd/m^2), L_{HDR}: luminance obtained from **HDR** image (cd/m^2)

The resulting calibration factors are variable from 1.2 to 2.0 depending on the luminance balance of the scene. A possible explanation for this might be the sensor of the camera isn't as precise as the luminance-meter sensor. It could be also due to inaccuracies in the placement of the reference points in the scene and luminance L readings and due to the limits of the dynamic range to reproduce a greater range of luminosity in scenes with high brightness variations.

- Camera settings for HDR images

The settings of the camera Nikon D60 are defined as follows:

- Aperture size =F 5.6
- Sensitivity: ISO= 400
- White balance of the camera: on, set for main light source in the scene
- Varying the shutter speed of the camera in manual mode: 5no. Exposure Values-EV are obtained
- The first value of EV is set at ±0.00 for each view direction
- Then, 2no. over-exposure are settled (EV: +1.00, EV: +2.00) and 2no. sub-exposure (EV: -1.00, EV: -2.00)
- 5no. Low Dynamic Range - LDR images are obtained: 3872 x 2592 pixels of resolution, as mean value

Materials reflectance

A reflectance survey was carried out to obtain the materials and surface reflectance values of interior architectonic elements. Luminance spot measurements were taken and compared with a reference reflectance material (Evans et al. 1999; Dubois et al. 2016).

Therefore, three readings with a luminance-meter (Gossen Mavo-Spot 2) were obtained from both surfaces in similar lighting conditions:

- A reference material with a known reflectance coefficient: colour grey card r=0,18 or 18%
- A material with reflectance is unknown

The reflectance survey was carried out in the final sample buildings and measurements were obtained as follows:

- Floors: measurements were taken in different areas of the court surface, to obtain reflectance variations according to different colours and finishes such advertising and track demarcations
- Interior walls and surrounding vertical surfaces in the court
- Spectator bleachers- seating area: measurements were taken in different areas of the bleachers

Note that bleachers are an important area of visual the field for both, players and spectators, including TV retransmissions, but with a high proportion of spectators, the reflectance value is variable, due to the presence of people, wearing different clothes and colours, instead of empty seats that present known reflectance properties and colour.

3.2.2 Simulations

In this first part of the research, the numerical simulations were carried out for enhancing the quantity and quality of data acquired and to increase the calendar of measurements (Atif et al. 1997). These simulations were carried out at CIHE, FADU, University of Buenos Aires with an international stay, see Appendix IV, section B, and section C4.

3.2.2.1 Photorealistic HDR rendering

Photorealistic HDR simulations allowed to estimate the reflectance and transmittance factors of architectonic surfaces and materials. These values are not possible to obtain from the site visits, such as ceilings, surrounding walls, glazing areas of toplighting and sidelighting openings. These factors were estimated and calibrated with the RADIANCE material library (LBNL 1995-2015 and 2000), adjusting colours and textures by comparison with photographs obtained in-situ.

The baseline models of the final sample are calibrated by in-situ measurements, for introducing daylighting strategies in the next Part, including the following:

- 3D virtual models
- Static simulations of real conditions by DESKTOP RADIANCE software (Marinsoft and LBNL 1998-2001, Version 2.0. Beta 2): INEFC and PEI buildings
- Scale model of INEFC building: E_h value and DF % in the court in diffuse light conditions, Artificial sky, direct and sunlight penetration patterns with Heliodon

3D virtual models

Two case studies of the final sample were built in AUTOCAD software (Autodesk Inc. 2000, Student Version) and stored in *.DWG format: the CEM EI, and INEFC buildings.

The virtual models were constructed containing the main architectonic elements, which defines the luminous space studied, such as floors, structure, exterior and interior walls, ceilings, and fenestration.

Static simulations

Then, in order to evaluate the luminance distribution in the user's visual field, static numerical simulations were carried out by DESKTOP RADIANCE software (Marinsoft and LBNL 1998-2001, Version 2.0. Beta 2), based on RADIANCE software algorithms (Larson and Shakespeare 1998).

The resulting *.HDR and *.PIC images were obtained to have a calibration for the real conditions in baseline scenarios to lately incorporate measures to improve the visual comfort, see Figure 3-14 and Figure 3-15.

These simulations also allowed to estimate the reflectance and transmittance factors of some architectonic surfaces and materials, which in the in-situ measurements were not possible to obtain, for example: ceilings, surrounding walls, glazing areas of top-lit and side-lighting systems. These factors were estimated and calibrated with the RADIANCE software (Larson and Shakespeare 1998) material library, adjusting colours and textures by comparison with photographs obtained in-situ. Horizontal illuminance E_h values in the court are also obtained by simulation in different sky conditions (overcast and clear skies), time and date of the year (21/12, 21/06 and equinoxes).

- Static simulation settings: 1st stage

The time and date of the year and parameters were simulated, according to the following:

- Simulation dates: 21/12, 21/06, 21/03 (Equinoxes)
- Simulation time: 10:00 am; 12:00 pm; 2:00 pm
- Sky conditions: Overcast, Clear
- Latitude: 41° North
- 3D Model format: *dwg
- Rendered Image format: *.hdr
- Image resolution: 1024 x 614

Scale model

With the aim to obtain values of E_h values and Daylight Factor- DF %, the INEFC building was built in 1:50 to perform simulations in diffuse light conditions with an Artificial sky, see Appendix IV-B. Studies of direct and sunlight penetration on the court were carried out in the Heliodon. In addition, HDR images of the INEFC scale model were also obtained in the artificial sky. This data was contrasted with in-situ measurements.

Figure 3-14. Comparison between images obtained by photo survey, top, and by simulation, bottom.

INEFC building (17/02/2008 12:45 pm, overcast sky), competition conditions render by Desktop Radiance software (Marinsoft and LBNL 1998-2001, Version 2.0. Beta 2)

Figure 3-15. Comparison between images obtained by photo survey and by Desktop Radiance software.

CEM PEI building (19/02/2008 10:45 pm overcast sky), training conditions and render by Desktop Radiance software (Marinsoft and LBNL 1998-2001, Version 2.0. Beta 2)

Figure 3-16. Scale model 1:50 of INEFC building, during measurements in the Artificial Sky, Habitat and Energy Research Centre - CIHE, FADU, UBA.

3.2.3 Visual comfort assessment

Objective and subjective assessments were carried out, after measurements and acquisition of objective and subjective data from reference and final samples were collected. The aim of the assessments is to characterize the luminous environment, evaluating how daylighting and interior architectural design impact on the visual comfort from the users' perception: athlete and spectator/remote spectator, including TV broadcasting. The visual comfort assessment was developed in two stages, as follows:

- Qualitative and qualitative visual comfort assessment: reference sample
- Detailed assessment of the field of view - FOV: final sample

3.2.3.1 Qualitative and qualitative visual comfort assessment

The basic assessment consisted in identifying the potential visual discomfort situations in the reference sample, in terms of the following parameters:

- Minimum illuminance level -E_h
- Uniformity - U
- Glare sources and excessive contrast

Minimum illuminance levels - E_h

The horizontal illuminance levels E_h and their distribution were obtained for 10no. buildings of the reference sample. The in-situ measurements were processed in a worksheet file to obtain maximum, minimum and mean E_h values in the court and seating areas. The values obtained were compared with the E_h minimum requirements according to the level of play.

Uniformity - U on the court

The uniformity indicates how the horizontal Illuminance is distributed on the court or playing area. The horizontal illuminance uniformity - U (0-1) is the relation between the horizontal illuminance average - $E_{h\ ave}$ and the minimum value of horizontal illuminance - $E_{h\ min}$, measured on the horizontal work plane.

The illuminance uniformity was obtained as a ratio between measured values of illuminance E as follows:

$$U_1 = \frac{E_{min}}{E_{av}}$$

Equation 3-2. Illuminance uniformity formula - U1, according to EN 67:1986 and EN 12193:1999.

Where:

E_{min} =minim illuminance measured at a point on the working plane, E_{av}= average illuminance measured at a point on the working plane

The horizontal illuminance uniformity U_1 was obtained for 10no. buildings of the reference sample from in-situ measurements, see section 3.2.1.1. The data was calculated by worksheet file, see Figure 3-5.

Glare sources and excessive contrast

The qualitative parameters assessed for each case study of the reference sample include the identification of sunlight penetration in the court, potential glare sources and excessive contrast in the users' FOV.

In addition, a diagnosis of visual comfort conditions in existing sports halls was completed to identify situations where the visual comfort can be disturbed by daylighting, see Chapter 5 and Appendix I.

3.2.3.2 Detailed assessment of the field of view -FOV

The luminance of the glare source is one of the major variables of discomfort glare, expressed as the source intensity in the observer viewing direction, per unit area of the source (Pierson et al. 2018).

The detailed visual comfort assessment is based on High Dynamic Range - HDR survey of the athlete and spectator/TV broadcasting field of view - FOV, in order to identify and quantify the following:

- Potential glare sources: luminance values and distribution
- Contrast, luminance L ratios and subjective brightness

The calibrated HDR images obtained were analysed to evaluate the athletes and spectators selected view directions and their field of view - FOV.

Due to the different sensibility of the human visual system, the analysis of regions of interest in the FOV (Inanici 2005b) was carried out, according to the following detail, see Figure 3-8. Accordingly, three areas or regions of interest were established and represented (Inanici 2005a, Inanici 2006) to accomplish the FOV assessment from the users' viewpoints, according to the following:

– Region or area 1: focus (2°) or target, foveal vision and maximum visual acuity

– Region or area 2: immediate surrounding up to 30°, binocular vision <60° horizontally, 50°-70° vertically

– Region or area 3: far or distant surrounding and background (>60°-100°), peripheral vision up to 90 ° -110 °, include the total field of view - FOV.

For the visual task performance, the most relevant regions considered are the focus or target and the immediate surrounding: areas 1 and 2, respectively.

It is considered that the visual task is performed mainly in areas 1 and 2 (focus and immediate surrounding areas). The distant surroundings are included in region 3 (background).

The average luminance values of the focus area 1, and the contrast ratio among architectonic surfaces were obtained for each image through PHOTOSPHERE software (Ward 2014, Version 1.8.16U).

HDR lighting data acquired was analysed by False Colour Visualization to show the range of luminances, see Figure 3-12. They cannot be displayed in absolute values and full range through conventional display devices or printed (Inanici, 2005b).

Potential glare sources: luminance values and distribution

Glare sources G_{source} and maximum luminances L_{max} values in the FOV were identified for each user: athletes and spectators, including TV broadcasting. The luminance threshold was established as >2.000 cd/m^2 in relation to the visual task (Wienold 2017).

The upper limit was set for each HDR image and potential glare sources are also verify that exceeds 7 times the task area average luminance (7x), according to Findglare (Ward 1993) from RADIANCE software (Larson and Shakespeare 1998), see *Equation 3-3*:

$$Glare_{source} \ * 7 \ (L_{task} \ )$$

Equation 3-3. Calculation to identify a glare source, based on Findglare default factor (Source: Ward 1993)

Where: L_{task}: luminance of the task (cd/m^2)

Contrast, luminance ratios and subjective brightness

The luminance contrast and frames were considered in the field of view - FOV to analyse spatial luminance variations, considering the target, near surrounding and background (Inanici 2005a; 2005b).

Accordingly, excessive contrast effect and adaptation levels were identified for each user, in relation within the FOV and considering the main view directions and the target during the visual task, see Equation 3-4.

$$C=\frac{L_{target}}{L_s}$$

Equation 3-4. Simple contrast with architectonic elements, based on contrast to describe subjective brightness (Source: Inanici 2005b, pp. 23)

Where:

C: contrast, L_t: luminance of the target or task (cd/m^2), L_s: luminance of the interior surfaces or architectonic elements (cd/m^2)

In order to identify potential adaptation glare situations in the FOV, excessive contrast was identified for architectonic surfaces by PHOTOSPHERE software (Ward 2014, Version 1.8.16U), measured in situ or calculated after calibration, see 3.2.1.2. For that, maximum luminance ratios in adjacent surfaces and simple contrast analysis of luminance values were calculated for athlete and spectator viewpoints, see Table 3-2.

The contrast ratio between the target and the architectonic surfaces was calculated providing numerical data, to investigate the adaptation of users during the dynamic visual task, according to Ding 2017, e.g.: the court floor, side walls, fenestrations, ceiling and seating area surfaces are the most common indoor surfaces affecting the users' FOV.

The relation between frames was also analysed. Maximum and minimum values of luminances from glazing openings against the adjacent opaque surfaces were obtained to identify potential hard frames in the FOV. For example, side walls, back walls and ceilings are considered as opaque surfaces.

Luminance maximum and minimum values are also shown in False Colour Analysis by PHOTOSPHERE software (Ward 2014, Version 1.8.16U), see Figure 3-12 and Figure 3-13. Their relative position in the visual field or FOV is also assessed, see Table 3-2.

CEM EI (19/10/2009, cloudy sky):

Court C4: 12:13 pm — Potential Glare Sourcess >(7x) **168**

Region		L In situ (1)	L HDRI (2)	Contrast ratio: target(1)	Contrast ratio: target(2)
1	Target (2º)	17	24	-	-
2	Ceiling		246	-	0,1
2	Glazing area window (near area)	1.478	2.170	61,6	90,4
2	Side Wall- concrete	54	111	2,3	4,6
3	Side Wall- orange	34	60	1,4	2,5
3	**Glazing area window***	**3.336**	3.330	139,0	138,8
3	Floor		129	-	5,4

* Calibration value

Frames	L max	L min	Contrast ratio:
Skylight opening/ adjacent ceiling	-	-	-
Windows opening/ adjacent wall	1.478	17	86,9

Table 3-2. Table showing the calculation of potential glare sources and simple contrast with the interior surfaces or architectonic elements in the Field of View – FOV: CEM EI building and C4 athlete view point.

Where:

$Potential\ Glare\ Sources > (7x)$: threshold obtained multiplying the luminance average value of the task L_{task} or target by 7 times

L_{task}: luminance of the target 2° (cd/m^2)

$L\ in\ situ\ (1)$: luminance value obtained from in situ spot measurements (cd/m^2)

$L\ HDRI\ (2)$: luminance value of interior surfaces obtained from HDR images after calibration by PHOTOSPHERE software (Ward 2014, Version 1.8.16U) (cd/m^2)

$Contrast\ ratio$: $(target\ 1)$*:* ratio between the target against L in situ (1) values, from architectonic elements located in regions 2 or 3

$Contrast\ ratio\ (target\ 2)$*:* ratio between the target against L HDRI (2) values, from architectonic elements, located in regions 2 o 3

$Region$: region or area location in the field of view - FOV, based on (Inanici 2005a)

3.3 2nd Part: Assessment of daylighting design strategies to improve visual comfort in sports halls using simulations and experimental test

Design strategies and measures were proposed in the final sample to be tested by users, based on the results of the users' visual comfort assessment and with the aim to improve the users' visual comfort conditions, see Table 3-3. It is organised in three phases, according to the following:

- Daylighting design strategies: 2 stages
- Simulations: photorealistic rendering
- Experimental test and user's preferences: 2 stages

Parts and phases		Goals	Stages	Procedures and metrics	Case studies	Outputs	Year
2nd Part - Assessment of daylighting design strategies to improve visual comfort in sports halls using simulations and experimental tests	DAYLIGTING DESIGN STRATEGIES	*Improvement of the users' visual comfort:* *daylighting design strategies* *+ measures*	*1st*	Daylighting design strategies + measures definition: • Array of 4/5 passive and active measures	Final sample	Annex IV-A AGAUR Scholarship 2011: LASH, ENTPE, France	2011
			2nd	Design guidelines for daylighting in sports halls in Catalunya: • *Guia de disseny de la il·luminació natural de pavellons esportius*		Design guidelines and recommendations: Annex I	2017
	SIMULATIONS	*Modelling of measures and real conditions:* *to display + to test*	*2nd*	Photorealistic HDR rendering, real and improved luminous scenes: • 3D virtual models • Static simulation • Luminance L calibration	Final sample	Annex IV-A AGAUR Scholarship 2011: LASH, ENTPE, France	2011-2012
	EXPERIMENTAL TEST	*Validation of measures by users:* *users' preferences: selection or rejection*	*1st*	Psycho-visual test, athlete and spectator viewpoints: • Paired comparison by panel • Statistics analysis			
			2nd	Quality evaluation of the users' survey: • Transcription of responses • Word frequency + strings analysis • User responses correlation with luminance L maps	Final sample	Discussion of results and partial conclusions	2013-2014 +2019

Table 3-3. Methodology proposed for the second part of the research: Assessment of daylighting design strategies to improve visual comfort in sports halls using simulations and experimental test.

3.3.1 Daylighting design strategies

With the aim to improve the visual comfort conditions in existing top-lit sports halls, a series of daylight design strategies and measures were proposed and developed, see Chapter 6 and Appendix IV, section A. Based on the results of the previous assessment in the reference and final sample, two stages were developed according to the following:

- Design strategies and measures definition: final sample
- Design guidelines for daylighting in sports halls in Catalunya

3.3.1.1 Daylighting design strategies + measures definition

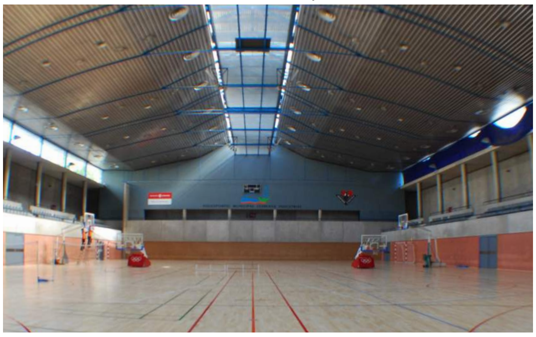
Design strategies and specific measures were suggested and tailored to each case study: PEI, PVH, INEFC and PEG buildings to be tested by users, considering the FOV of athlete and spectator. These measures included different solutions with the aim to improve the visual comfort, such as integrating sunshade and daylight control devices, modifying glazing transmittance factors, colours and reflectance factors, see Chapter 6 and Appendix IV, section A.

Design guidelines for daylighting in sports halls in Catalunya

After concluding the 1st Part and partially the 2nd Part of this work a daylighting design guidelines for sports halls in Catalunya was compiled, including the most preferred luminous environments from the test results.

Athlete viewpoint

Spectator - TV broadcasting viewpoint



a) Real conditions by photo survey

a) Real conditions by photo survey

b) Real conditions by static simulation: baseline case

b) Real conditions by static simulation: baseline case

Figure 3-17. Images of the CEM EI sport building showing the baseline cases: a) real conditions obtained by photo survey and b) renders obtained by simulation.

Athlete viewpoint, left, and spectator-TV broadcasting viewpoint, right.

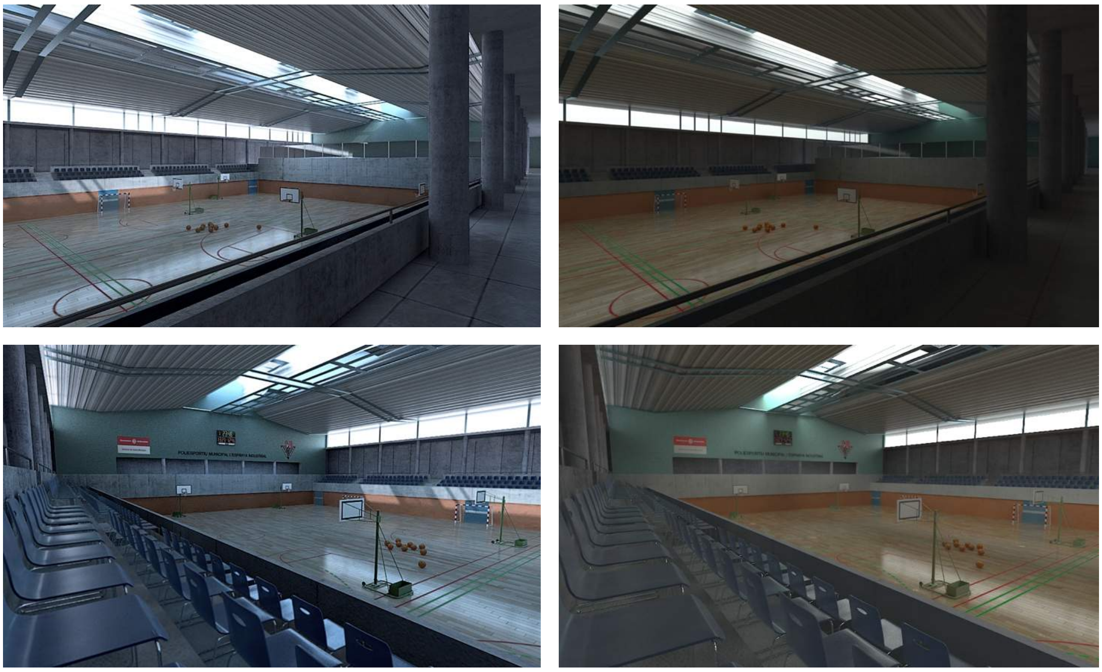


Figure 3-18. HDR images obtained by simulation from spectator viewpoints of the CEM EI building: after post production, left, and before post production or final results, right.

The purpose of these guidelines is to help designers with the integration of natural light in sports halls facilities in Catalunya, considering the users' preferences for visual comfort. It could be relevant for both new and rehabilitation projects, see Appendix I: Guia de disseny de la il·luminació natural dels pavellons esportius (Gonzalez Matterson 2017).

These guidelines included an inventory of frequent situations found in the reference sample, considering the visual comfort in the reference sample. They comprise four main parts, according to the following sections:

- Part I: Basic concepts of natural light and visual comfort
- Part II: Daylighting systems in sports halls: frequent situations of visual discomfort
- Part III: Daylighting design strategies for sports halls
- Part IV: Daylighting design strategies and verification: simulations and monitoring

3.3.2 Simulations

Numerical simulations were carried out to test the efficacy of the measures proposed with the aim to improve the visual comfort in the reference sample. To investigate also the preferences of users in sports halls under natural light conditions.

3.3.2.1 Photorealistic HDR rendering

Accurate and realistic images were simulated to perform an experimental visual test, where the user made decisions about different scenes or images displayed, see Appendices IV-A and Appendix III for full results.

The simulations process was organized in three phases, according to the following:

- 3D virtual models
- Static simulation
- Luminance L calibration

These HDR images obtained were calibrated to be the stimuli to study the panel's preferences with different luminous scenes: existing and improved luminous conditions.

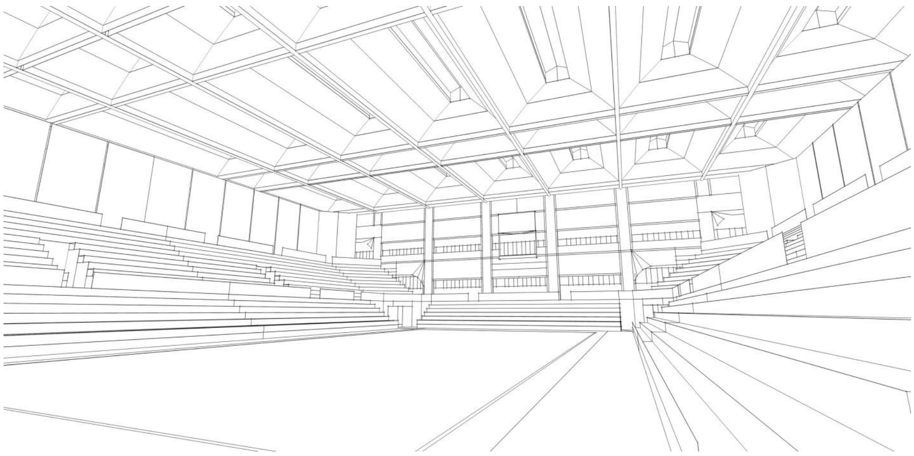


Figure 3-19. Interior view from the court of the virtual model of PEG building in *DWG with main architecture elements and measures incorporated: modification of the ceiling.

3D virtual models

The CEM EI, CEM VH, INEFC and PEG buildings were built and stored in *.DWG format. These virtual models were built with the main architectonic elements of the court and surrounding seating area, as: floors, structure, exterior and interior walls, ceiling, and fenestrations.

After the virtual 3D models were completed, the process of realistic rendering started.

Once existing conditions were completed, a visual verification was carried out to achieve the optimum level of accuracy of the images. The resulting renders were also visually compared with the HDR images obtained from real or existing conditions in the case studies. A maximum level of interior details was included in the 3D models to obtain the baseline scenarios, e.g.: bleachers seats, baskets, backboards, rims, balls, advertising signs and logos, see Figure 3-17.

A post-production operation was used to improve rendered images obtained, see Figure 3-18.

The rendering process to incorporate the suggested daylight design strategies and measures started after the baseline scenarios were adjusted with photographs and HDR images taken in-situ, see Figure 3-21.

A total of 16no. HDR images were rendered for existing conditions. 5no. different scenarios with improvements were rendered for PEI, PVH and PEG and INEFC buildings, and 4no. scenarios for INEFC building were obtained for each user and condition: athlete and spectator/TV broadcasting viewpoints, resulting in 38no. HDR images.

- Numerical simulation parameters

The CIE standard overcast sky condition (Moon and Spencer model, cited in Reinhart et al. 2006) was selected to perform the simulations, where the luminance distribution in the sky is three times brighter near the zenith than at the horizon. This model was selected to consider the glazing areas as potential sources of glare by diffuse light. Because of the expected difficulty of multiple rendered images realization to compute the sunlight penetration during the day and seasonal variations, the influence of direct light or sunlight is not considered.

The photorealistic simulations were obtained and stored in *.hdr format, according with the following simulation parameters:

- Simulation date: 30 April - Spring, equivalent to 30 July - Summer
- Simulation time: 12:00 PM
- Sky conditions: Overcast CIE Standard
- Sky luminance max. value: 20.000,0lx
- 3D Model format: *dwg
- Image resolution: 1024 x 614

Luminance L calibration

Different parameters were adjusted for the images obtained, in order to reproduce the same amount and distribution of light than in the real-world scenes ((Villa, Parent and Labayrade 2010; Villa and Labayrade 2011; 2012). The goal was to obtain the same amount of light hitting the user's eye during the experimental test.

Thus, images were calibrated by tone mapping with luminance reference values obtained from in-situ measurements, see section 3.2.1.2 and Figure 3-12.

The calibration procedure by tone mapping was completed in the following steps:

Step 1: the simulated baseline scenarios were adjusted to the luminance L reference values and HDR obtained by in-situ survey.

Step 2: the simulated scenarios with the addition of design measures were adjusted by comparison with the calibrated baseline scenarios.

Step 3: the display device and the position of the subject were adjusted with the comparison of luminance-meter readings from the screen and the luminance L reference values obtained in-situ. The tone mapping for each simulated HDR images was adjusted and calibrated with luminance L values obtained in real conditions, see Figure 3-21.

- Experimental test and user's preferences

To objectively evaluate the effectiveness of the visual comfort measures, suggested in the previous section 3.3.1, an experimental psycho-visual test was proposed and designed. The test included different daylight scenes or environments to be evaluated by users in two situations: athletes and spectators /TV broadcasting. Moreover, the test results could provide a validation or not about the measures incorporated, plus offering additional information concerning which aspects users considered more significant to achieve a comfortable luminous environment in top lit sports halls. Accordingly, the experimental tests were carried out in two stages, as follows:

- Psycho-visual test
- Qualitative evaluation of the users' survey

3.3.2.2 Psycho-visual test

The psycho-visual test was designed to qualify and quantify by users the existing conditions versus the suggested daylight measures in four buildings of the final sample. Their preferences for alternative luminous environments or luminous scenes under daylight were also assessed. The experiment was developed in two phases, according to the following:

- Paired comparison by panel
- Statistics analysis

The goal of the experimental test was to enable the panel to have the same experience than in real conditions, in terms of quantity and quality of light. For that purpose, images were calibrated with in situ measurements. The simulated images or stimulus were compared and selected or rejected by panel, considering the real performance against the feasibility of the visual comfort improvements for both users:

- Athletes in training conditions
- Spectators in competition conditions

In order to avoid any biases or pre-determined by order of appearance, the stimuli were presented to subjects randomly, recreating either the real performance of daylighting systems or current operation and the measures integrated in the final sample. Additionally, the users had to complete a series of questionnaires to justify their decisions with open-ended and close-ended questions, to obtain more information about their preferences and rejection criteria.

Then, a statistical analysis of the results was carried out, to obtain the most and least preferred luminous environments, identifying groups of subjects who shared the same opinion in their judgments (Villa, Parent and Labayrade 2010; Villa and Labayrade 2011; 2012; 2014).

HDR image by static simulation:
skylight without shading device
baseline = real scenario

HDR image by static simulation:
skylight + shading device vertical blades 0º
scenario 1= with improvements

HDR image by static simulation:
skylight + shading device blades 50º
scenario 2= with improvements

HDR image by static simulation:
skylight + shading device blades 45º
scenario 3= with improvements

Figure 3-20. HDR images obtained by simulation from spectator viewpoints of the CEM EI building: baseline and improvements included in scenarios 1, 2, 3

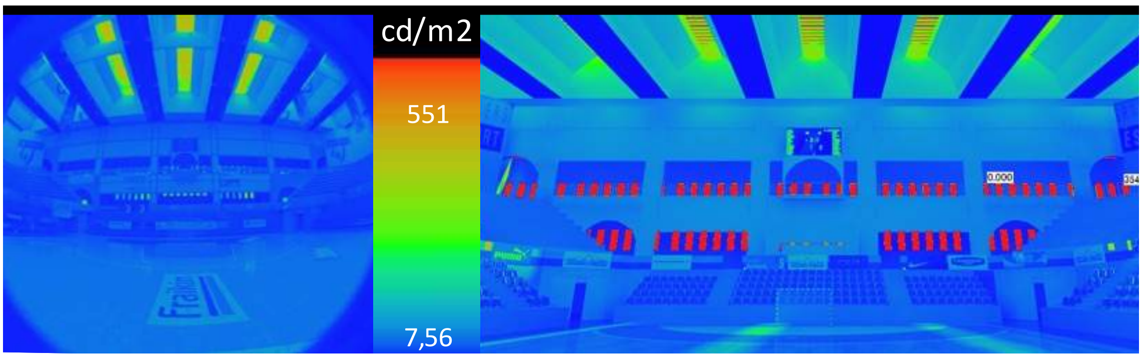


Figure 3-21. HDR images of athlete viewpoint after calibration in False colour: obtained in situ, left; and, obtained by simulation, right.

The test was developed and carried out in the LASH, ENTPE, University of Lyon, see Appendix IV, section A and Appendix IV, section C (Gonzalez Matterson and Fontoynont 2011).

Paired comparisons by panel

Different scenes or images were shown as stimuli to allow subjects to make decisions. The Thurstone's protocol[1] of paired-comparisons of a set of stimuli was implemented. This protocol allowed the subjects to evaluate two different stimuli at a time and choose one of them.

The number of pairs to be compared for ***n*** stimuli (Villa et al. 2010; Villa and Laybarade 2012; 2014) is calculated, according to Equation 3-5.

$$Nº\ of\ pairs = \{[n\,(n-1)]/2\}$$

Equation 3-5. Number of pairs resulting for n stimuli for the Thurstone's paired-comparison protocol.

As a result, 6no. rendered images were obtained for each user' viewpoint, so the number of pairs to compare results in 15no. for each case studies of the final sample: CEM EI, CEM VH and PEG building. For the INEFC test series N° 3, 5no. rendered images were obtained, which results in 10no. pairs to compare for the athlete viewpoint.

- Design of the test

In order to limit the fatigue of subjects performing the comparisons, 8no. sub-set or test series were designed. Each test series corresponded to one case study and to one of the two viewpoints: athlete or spectator/ TV broadcasting. Accordingly, the test was organized as follows:

- Test N° 1 CEM EI - Athlete viewpoint
- Test N° 2 CEM EI -Spectator viewpoint
- Test N° 3 CEM EI - Athlete viewpoint
- Test N° 4 CEM EI -Spectator viewpoint
- Test N° 5 CEM EI - Athlete viewpoint
- Test N° 6 CEM EI -Spectator viewpoint
- Test N° 7 PEG - Athlete viewpoint
- Test N° 8 PEG -Spectator viewpoint

Accordingly, each test series had 15 pairs, except the Test n° 3 with 10no. pairs. As a result, each subject performed a total of 115no. pairs of comparisons, see Appendix IV-A. The test was elaborated for the presentation in random order for each participant (Villa et al. 2010): the test series or case studies, including users' viewpoints, as athlete and spectator, and images A or B.

- Questionnaires

The design of the questionnaires was based on the psycho-visual tests experience of the LASH (Villa et al. 2010; Villa and Labayrade 2012; 2014) with open-ended and closed-ended questions.

Three different questionnaires were designed to fill-in by subjects to obtain more information about users' preferences and rejection criteria, see Table 3-4 and Appendix IV-A, pp.48-51.

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[1] The Law of comparative judgment. This allow the post Analytic Hieratical Process, to evaluate alternative solutions for the same question. The selection of one alternative from a given set of alternatives (Thurstone, L. 1927 cited in Villa et al. 2010)

	Nº of surveys	Type of questions	Nº of questions	Question topic
Nº 1 Test series questionnaire	8	Close ended 4 options	2	Realisation of the test: level of difficulty/easy Comfort during the test: uncomfortable/ comfortable
		Open ended	3	Justify your response about test realisation. Justify your preference criteria Justify your rejection criteria
Nº 2 Final questionnaire	1	Close ended 4 options	3	If the images' brightness was realistic. If the subject was dazzled or not during the test. If the subject was bothered by the high brightness of the screen
		Close ended Yes/ No	1	If the subject feels physical discomfort as a result of the test experience
		Open ended	1	If the previous answer is yes, what kind
Nº 3 Participant information questionnaire	1	Open ended	4	Surname, Name, Age, Professional activity
		Close ended Yes/ No	1	If the subject has previous knowledge of lighting
		Close ended 2 options	1	If the previous answer is yes, which one
		Open ended	1	Others, specify
		Close ended Yes/ No	1	If the subject wear glasses or contact lenses.
		Close ended 4 options	1	If the previous answer is yes, specify your vision problem
		Open ended	1	Other, explain
		Close ended 5 options	1	How many psycho-visual tests have done the subject at LASH (2009-2011)

Table 3-4. Resume of the three different questionnaires presented to the panel during the pyscho-visual test realization.

Open-ended questions were introduced in the questionnaires to obtain a quality survey data and to not limit, induce or suggest the answers of subjects by the researcher (Foddy 1993: 127, cited in Reja et al. 2003)[2], as follows:

Nº 1- Test series questionnaire: subjects were invited to explain their choices, after each series were completed, filling-in in 8no. questionnaires to obtain:

- The preferences and rejection reasons given to judge the images of the series
- The subject's opinion about the level of difficulty/easily to choose each image

[2] According to close-ended questions limit the respondent to the set of alternatives being offered or suggested by the researcher. This has several consequences for the quality of survey data, because the responses are induced by the researcher. However, offer a low level of complexity analysis, low level of dispersion and missing data.

N° 2 - Final questionnaire: it was designed to obtain information about whole test experience by subjects, including:

- Parameters to classify the level of difficulty/easily to conclude the test, and if subjects present any annoyance or discomfort by luminances: glare perception
- Parameters about the level of quality of images: if the images are realistic, level of detail in the images

N° 3- Participant information: the final questionnaire was requested to the subjects at the end of the test, related to personal data as gender, age, profession; and skills and if the subject was wearing glasses/contact lenses, if they had previous knowledge about lighting.

- Stimuli: HDR images by simulation

The stimuli presented to subjects were the realistic images obtained in the second stage of simulations, see Appendices IV, section A and III, recreating the real performance of daylighting systems or current operation and the measures incorporated into the final sample: PEI, PVH, INEFC, PEG; from two viewpoints: athlete and spectator- remote spectator/ remote spectator and TV broadcastings.

The images or stimuli were presented randomly to the subjects in equal number of times to perform the comparisons, asking the questions according to the athlete or spectator point of view. To avoid biased answers, the same image is randomly displayed as A and B in different pair of comparisons, see Figure 3-23.

The simulated images of the four 4 buildings of the final sample resulting in six 6 for each viewpoint: 1 one of real conditions, and 5 five with improvements. As a result, a total of 54 HDR images obtained to perform the test, see results in Appendix III.

- Test procedures

The psycho visual test was performed to obtain the most preferred luminous environments and record the panel choices considering the visual comfort in two different situations: as athletes in training conditions, and as spectators in a competition.

The tests were performed in 4 phases, with a duration of approximately one hour per participant, according to the following, see Figure 3-24.

Phase 1: an oral explanation and printed questionnaire was given to subjects. Then, participants were invited to imagine themselves in each sports hall in two situations:

- Playing sports (e.g.: basketball, handball, volleyball, fencing, etc.)
- Watching the competition (e.g.: basketball, handball, volleyball, fencing, etc.)

- Playing sports, athlete viewpoint
  - FR: "*Selon vous, quelle ambiance lumineuse vous paraît la plus adaptée pour pratiquer un sport?*" (original language of the test),
  - EN: According to you, which lighting environment is the most suitable for playing sports? (translation by the author)

- Watching the competition, spectator/ TV broadcasting viewpoint
    - FR: *"Selon vous, quelle ambiance lumineuse vous paraît la plus adaptée pour regarder la compétition?"* (original language of the test),
    - EN: According to you, which lighting environment is the most suitable for watching the competition? (translation by the author)

Phase 2: the photorealistic images were retro-projected on the screen, using a display device capable of producing up to 10,000 cd/m^2. The subjects were able to manage the amount of time they can see each image, A or B, with the track pad or the keyboard.

Phase 3: subjects were asked to choose between image A and image B by answering the previous questions for each test series. The panel choices were given orally or 'a viva voce' and recorded in a matrix by worksheet file. After the sequence of images of each series were finished, participants were invited to answer two different questionnaires about the choices made, the questionnaires n° 1 and n° 2.

Phase 4: participants were invited to fill-in questionnaire n° 3 about the whole experience after completing the viewing session of the 8-test series, and once the test was concluded.

- Room test configuration

Participants were facing the screen and sitting in a chair with a desktop and a keyboard to control the image visualization on the screen. After the calibration process, the optimal distance between participants and the display device is set out.

Thus, the screen and the chair were fixed to the floor, to avoid variations on distance and position during the test. Participants were sitting in fixed position with respect to the display device (2,00 meters of distance). The desk is movable, according to the participant preferences.

- Luminous conditions during the test

The luminous conditions of room during the test were according to the following, see Figure 3-24:

- Phase 1 - general explanation and oral presentation of the test: ceiling lights on
- Phase 2 and 3 - images' display: ceiling lights off and table lamp off with total dimming of the room, both natural and artificial lighting
- Phase 4 - to complete the questionnaires, 1, 2, and 3: table lamp on

- Equipment used for tests

The equipment used for the test was the following:

- Dedicated room of the LASH laboratory
- Display device of the LASH laboratory, capable for display up to 10,000 cd/m^2 to retro-project images on the screen
- Flat screen (2,40 m x 1,50 m)
- Desk, table lamp and chair: where participant performed the test
- Personal laptop HP-Compaq Intel Celeron CPU 560 @2.13 GHz, 0,99 GB RAM, Microsoft XP Professional Service Pack 3 (Version 2002), to control the display of each test series and register the responses in a worksheet file

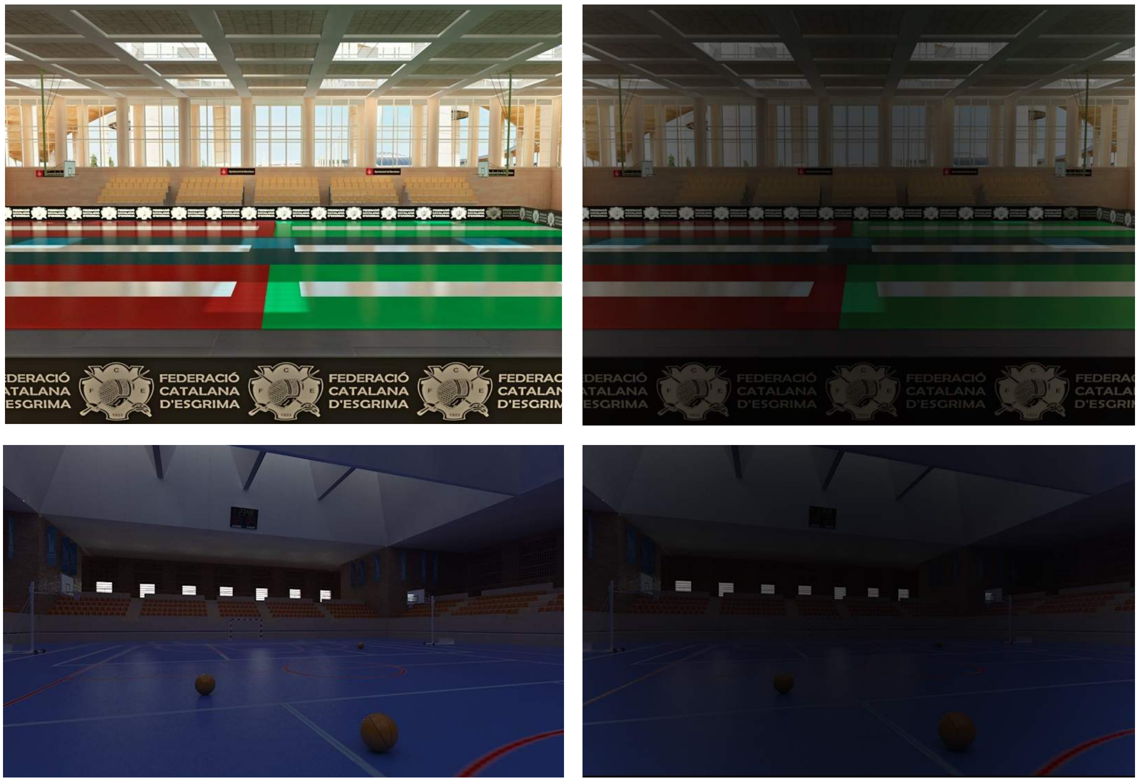


Figure 3-22. HDR images obtained by simulation for the final sample, before and after the tonne mapping calibration for display.

Top: HDR Images obtained by simulation for spectator point of view in INEFC building: before calibration, left, and after tonne mapping, right. Bottom: Images obtained by simulation for athelete point of view in CEM VH building: before calibration, left, and after calibration, right.

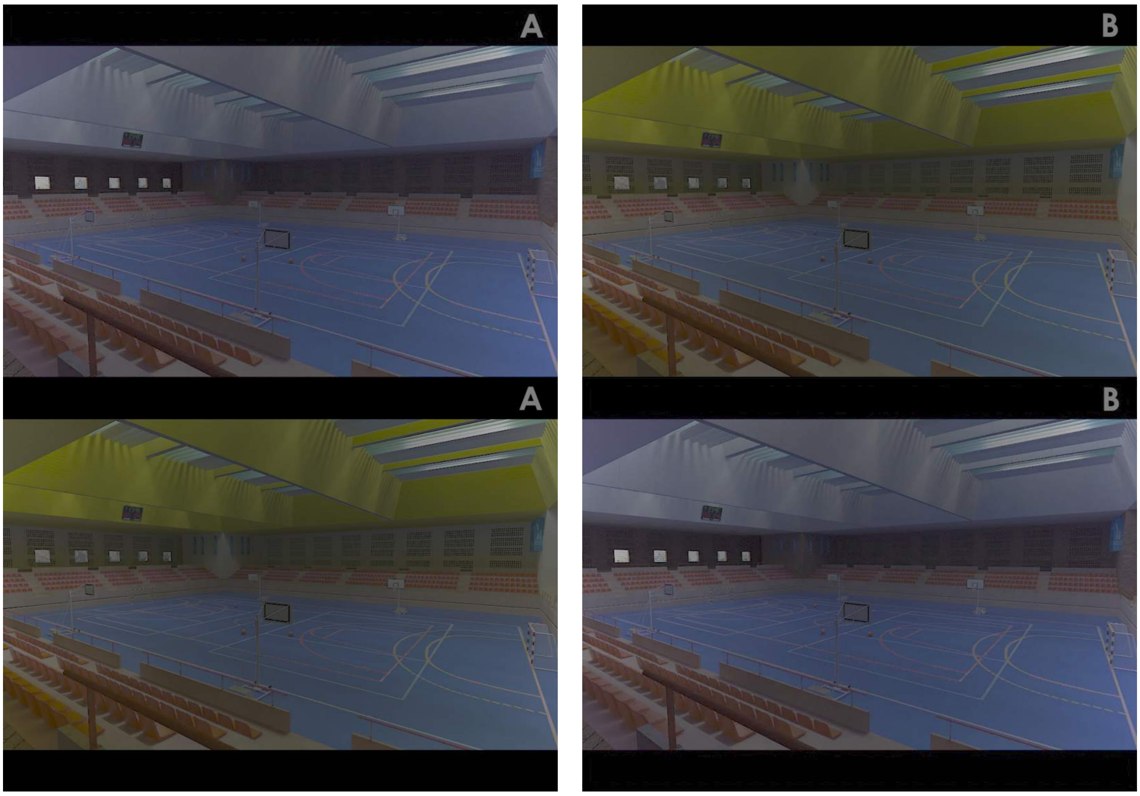


Figure 3-23. Example of pair of images, randomly and equally displayed during the test as A and B.

Statistics analysis

The resulting preferences matrix was processed by statistical toolbox software to extract the most and less preferred images, which contained 3680 no. subjects' choices. From this matrix, scale mean values of the hierarchical clustering were extracted by Thurstone comparative judgment, law case V (Thurstone 1927, cited in Villa et al. 2010).

The statistical analysis was made to identify groups of subjects who shared the same opinion in their judgments (Villa and Labayrade 2012; 2014). If the case of two or more groups extracted, they are analysed in separate groups.

Later, the mean values for each series and each group was obtained, resulting in a ranking of images ordered from the most preferred to the less preferred.

3.3.2.3 Qualitative evaluation of the users' survey

In order to extract the key words and valuable information about visual comfort scenes preferences and dislikes, the qualitative evaluation of the survey responses was completed to describe the test results from the users' subjective perception.

The panel responses were evaluated to obtain a justification of users' choices for the most comfortable luminous environments in top-lit sports halls. This analysis allowed to get a more accurate approach from the users' subjective perception, considering the users' visual preferences and rejection criteria.

The aim was to link to the choices made by the panel (subjective) with objective data from False Colour Analysis of luminance mapping, in terms of luminance distribution, maximum and minimum values. Accordingly, survey results from users' subjective perception were correlated with the objective analysis of the L luminances in the FOV.

The qualitative analysis was processed in different steps, with the aim of obtaining a word frequency and word string analysis in the original French language:

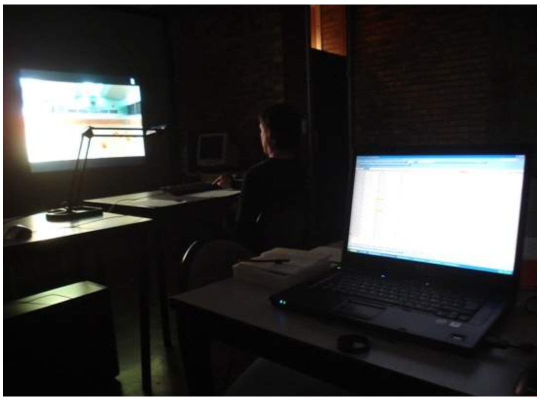
- Transcription of responses
- Word frequency and strings analysis
- Translation: from French to English

Items	(FR) original source	(EN) translation
1	Quantity of light category	
L	Luminosité, lumière, éclairage	Light, luminosity, brightness, lights, daylight, lighting, lighting level
No SH	Pas d'ombre, sombre, obscurité, noir	No sombre, shade, shadow, dark, darkness, gloom, black
SH	Trop d'ombre, sombre, obscurité, manque de lumière	Too much sombre, shade, shadow, dark, darkness, gloom, lack of light
L min	Lumière/ éclairage: peu, minimum, trop faible	Level of light: low, minimum, too low/weak/poor
L dif	Lumière/ éclairage: tamisé, diffuse, atténué, douce	Light filtered, diffuse, dimmer, soft, gentle
L ave1	Lumière, lumineuses éclairage: mais pas trop	Level of light: average, bright but not too much
L ave2	Lumière, éclairage: assez, suffisant, bien, bonne	Level of light: good, adequate, enough
No L ave2	Lumière, éclairage: pas assez, pas suffisant	Level of light: not good, not adequate, not enough
L Max	Lumière, éclairage: plus, forte, importante	Level of light: maximum, large, significant amount
L dir	Lumière, éclairage: trop directe, vive, agressive	Level of light: too direct, strong/bright, aggressive

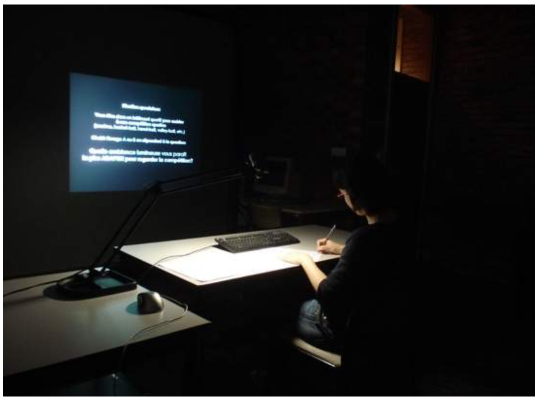
Table 3-5. Table showing the most referred items or lexical words identified, from the open-ended responses: quantity of light category and sub-categories: original language (FR) and translation by the author (EN).

1- General oral explanation of test and series' and printed questionnaires were given to subjects

2- Photorealistic images were displayed during each series, to choose A or B by subjects



3- Responses A or B were recorder in a matrix by Excell software (*.xl file)



4- After the finalization of each series (8), the panel have to justify their choices

Figure 3-24. Images showing different phases of the psycho-visual test and lighting room configurations, carried out in the facilities of LASH-ENTPE, University of Lyon.

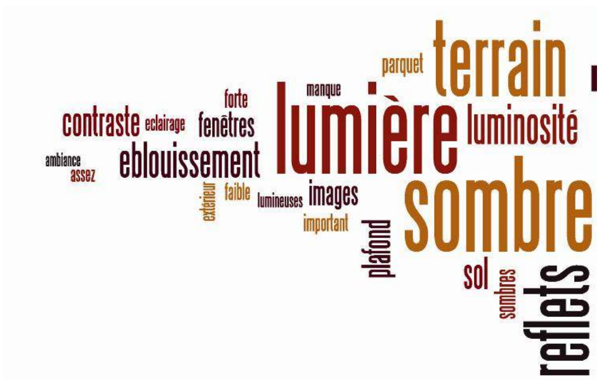


Figure 3-25. Word clouds with word frequency analysis of open-ended responses in French language: preferences, left, and dislikes on the right.

Big size words represent the most frequent, small size the less frequent word to analyse survey responses

Transcription of responses

A total of 256no. responses were collected from questionnaires n° 1 and 2 and obtained at LASH-ENTPE, see Appendix IV, section A. After the stay, the open-ended responses were transcripted from manuscripts into a word processor and worksheet files to perform a qualitative analysis.

Word frequency and strings analysis

The open-ended survey responses were analysed in the original language (French) For that, the series questionnaire n° 2 was analysed to obtain qualitative information to justify the users' criteria to make choices for the most and less preferred images. The analysis was based on extracting a word frequency, key words and lexical items, from a word-based analysis approach (Ryan and Bernard 2000, cited in Jackson and Trochim 2002).

- Word frequency analysis

The word frequency analysis was performed to extract the first 25, 50 and 100 most used words from the open-ended questions. The basic analysis was completed by Online-Utility.org software (Adamovic 2009, version 2) and organized in three main groups, according to the following: a) Images selection, b) Most preferred images and c) Less preferred images or rejection.

Then, the most frequent words were shown in word clouds and translated to English by the author. Lexical density and number of sentences were also extracted. Word filters were applied for articles, prepositions, affirmation, negation, augmentative, and diminutive adjectives, for example: le, les, des, trop, beaucoup, peu, plus, sans, pas, etc. These words were studied in context in next phase.

- String analysis: key words in context

In order to understand and categorize the subjects' judgments, a text analysis was processed to extract key words, themes and categories from the statements (key words in context KWIC or co-occurrences of words). In order to discover the logical progression of ideas that support the users' choices, key words extracted previously were studied in context and the analysis was organized in two steps:

- To classify units or items to obtain the most common key words, according to the categories identified
- To analyse them in context or their co-occurrences with other key words.

After that, the similar concepts were organized into piles or clusters and the number of times these units appear in the text were extracted. Likewise, correspondences and interlinks with other items or concepts were also investigated.

For that purpose, the key words or lexical items with similar significance were grouped in categories and subcategories. Co-occurrences of words or strings with similar significance were also extracted, as explained in the most frequent word analysis. The next example illustrates the analysis carried out in the sentences extracted:

- *"Bon éclairement mais pas trop"*, FR. Good lighting level, but not too much, EN.

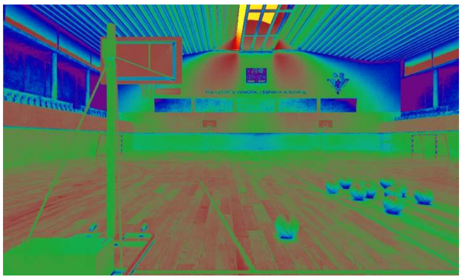
It is assumed by the author that in this sentence there are two ideas:

- <Good lighting level> as "average2 level of light" (1st idea or main concept)
- <No too much light> as "average1 level of light" (2nd idea or secondary condition after the main concept is fulfilled).

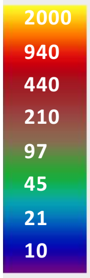
Test results: Athlete

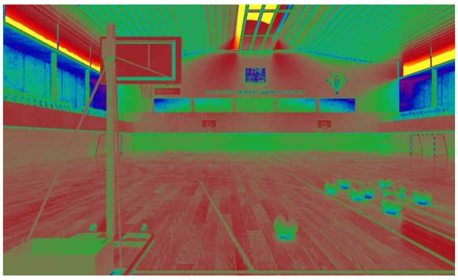
Most preferred images	**Less preferred images**

Case of study: CEM EI – Test series nº 1. Athlete point of view, group 1 (25 subjects)



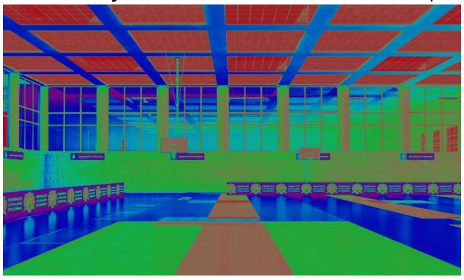
CEM EI- Image 4- Improvement measures in lateral windows: transmission glass coefficient 20%.



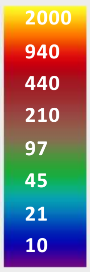


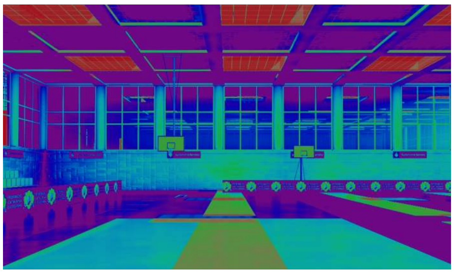
CEM EI- Image 1- Reference image, real situation. Lateral windows, transmission glass coefficient 85%.

Case of study: INEFC M– Test series nº 3. Athlete point of view, group 1 (24 subjects)



INEFC- Image 5 - Improvement measures in top lit system: addition of artificial lighting in opaque ceiling surface: 500 luminance level.





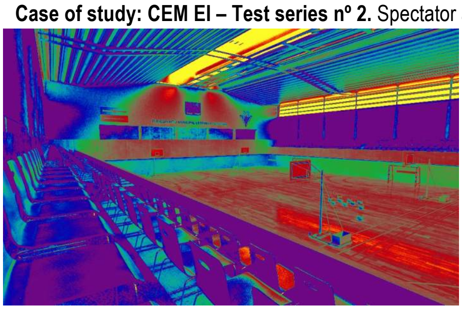
INEFC- Image 2 Improvement measures in lateral windows, transmission glass coefficient 20%.

Figure 3-26. Results of the most and less preferred images in False Colour Analysis (cd/m^2): athlete user

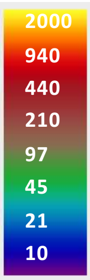
Test results: Spectator and TV broadcasting

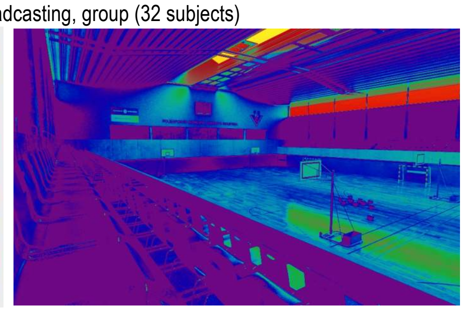
Most preferred images	**Less preferred images**

Case of study: CEM EI – Test series nº 2. Spectator and TV broadcasting, group (32 subjects)



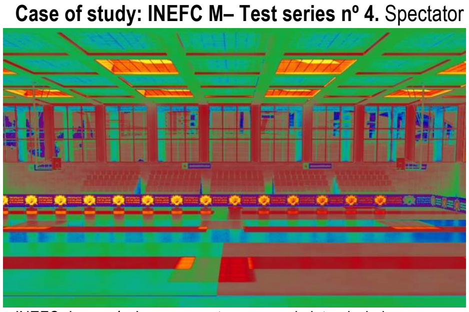
CEM EI**- Image 6** - Improvement measures in top lit system: solar shading device (zenith: 4 Nord and 4 South, orientation 40°), increasing glazing area (7,80 width), glass transmission coefficient: 85%. Improvement measures in lateral windows: solar shading device Nord and South (3 blades, orientation 0°)



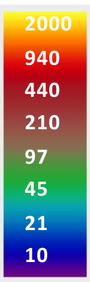


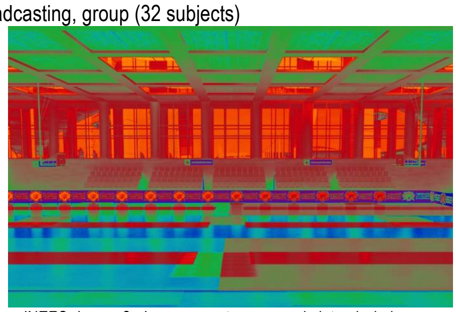
CEM EI**- Image 5** - Improvement measures in top lit system: solar shading device (zenith: 4 Nord and 4 South, orientation 40°), glass transmission coefficient: 85%. Improvement measures in lateral windows: solar shading device Nord and South (3 blades, orientation 0°)

Case of study: INEFC M– Test series nº 4. Spectator and TV broadcasting, group (32 subjects)



INEFC- Image 4 - Improvement measures in lateral windows, transmission glass coefficient 40%





INEFC- Image 2 - Improvement measures in lateral windows, change of panoramic view (without near exterior elements)

Figure 3-27. Results of the most and less preferred images in False Colour Analysis (cd/m^2): spectator user

- Translation

The key words, strings, categories and subcategories extracted from responses were translated and interpreted from French to English by the author (WordReference 2020).

Users' responses correlation with luminance maps

The real conditions and the most preferred images obtained by simulation were evaluated in order to identify the luminance L distribution, L contrast and glare in the field of view – FOV. This analysis was carried out by "Image Analyser" of DESKTOP RADIANCE software (Marinsoft and LBNL 1998-2001, Version 2.0. Beta 2) and PHOTOSPHERE software (Ward 2014, Version 1.8.16U). The images were presented in False Colour Analysis, see Chapter 7, see Figure 3-26 and Figure 3-27.

3.4 3rd Part: Application of daylight design strategies: new sports hall in Tarragona

In the last part of this work, the methodology designed for this research and the partial outcomes of the daylighting design strategies and measures was implemented in the design of a new sports hall in Tarragona, with a central skylight: the Palau d' Esports Catalunya. Accordingly, this part was developed in two stages as follows, see Table 3-6:

- Skylight optimization
- Post Occupancy Evaluation- POE: 2 stages

Parts and phases		Goals	Stages	Procedures and metrics	Case studies	Outputs	Year
3rd Part - Application of daylighting design strategies in a new sports hall for the Tarragona 2018 Mediterranean Games	APLICCATION + VALIDATION	*Daylight optimization* *+ design strategies implementation* *+ verification*	*1st*	Skylight optimization: • Dynamic lighting simulations by DAYSIM software • Daylight design recommendations	Palau d' Esports de Catalunya	Annex IV-D	2015
			2nd	Post Occupancy Evaluation- POE: • 1st campaign of POE: E_h measurements + HDRI survey by luminance camera Coupled Charge Display – CCD • 2nd campaign of POE: spectator' visual comfort survey (during the 2018 Tarragona Mediterranean Games)	Palau d' Esports de Catalunya	Annex IV-D Discussion of results and final conclusions	2017-2018

Table 3-6. Methodology scheme proposed for the third part of the research: Application of daylight design strategies in a new sports hall for the Tarragona 2018 Mediterranean Games.

3.4.1 Skylight optimization

Daylight optimization of the central skylight was carried out, during the design phases of the new Palau d' Esports Catalunya- PEC. The goal of the daylight optimization was to develop and verify the optimal solution for the central skylight proposed by the design team for the new sports hall (Gonzalez Matterson and Salom 2015). The optimization was carried out in two phases, according to the following:

- Dynamic lighting simulations
- Daylighting design recommendations

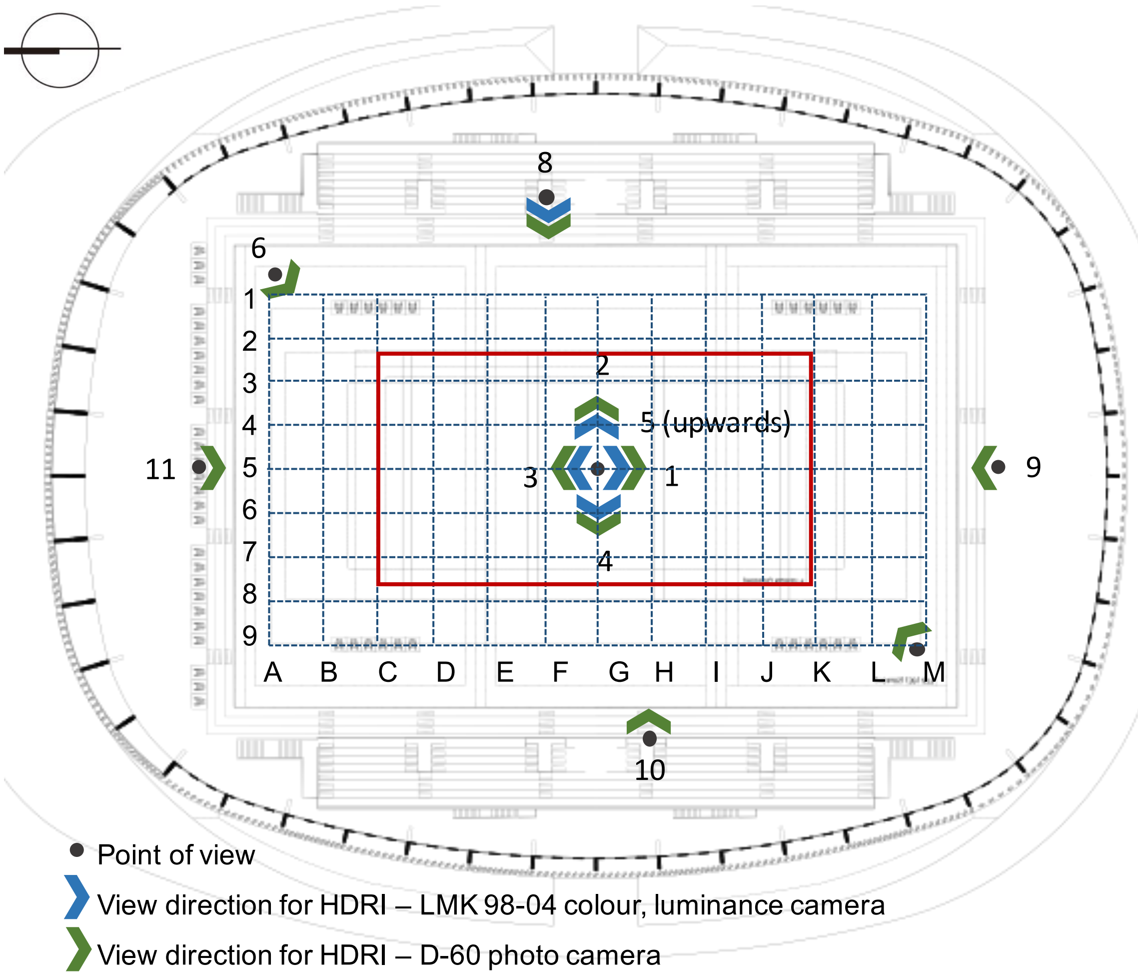


Figure 3-28. Floor plan layout of the PEC showing the orthogonal grid and viewpoints /view directions for in-situ measurements.

1st Campaign of POE carried out during 2017 (Source: González Matterson, Salom and Ortiz 2017, pp.9).

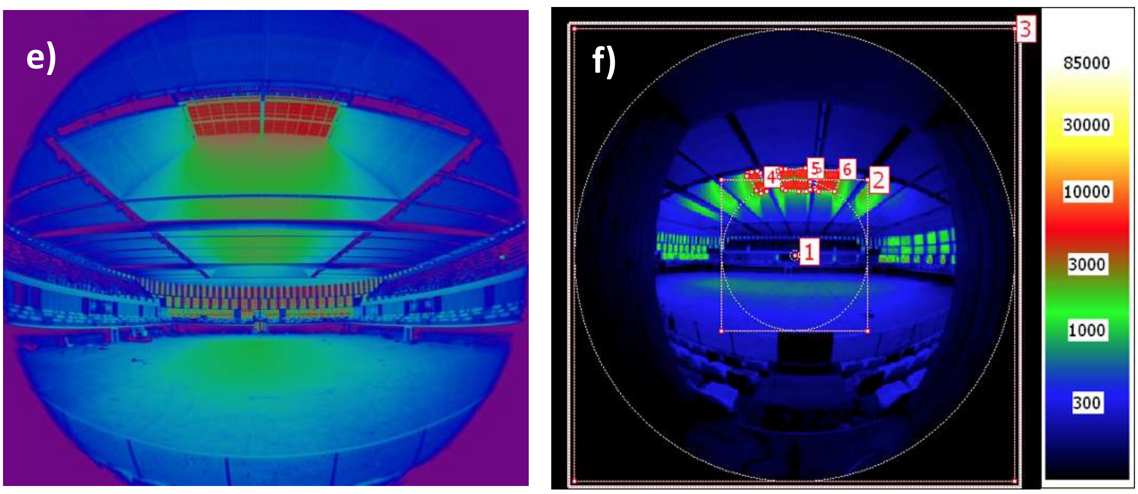


Figure 3-29. HDR images obtained in the Palau d'Esports Catalunya by the 1st Visual comfort campaign of the POE: spectator/TV point of view (Source: González Matterson, Salom and Ortiz 2017, pp.23, 26).

HDR Images in False Colour Analysis obtained by photographic camera, left and by luminance video camera –CCD, right

Analysis and assessment of graphic and design project documentation, technical meetings, dynamic simulations and the elaboration of technical reports were carried out during the design phases of the PEC, in 2015. Preliminary and final reports were elaborated and presented, containing simulation results and daylighting design strategies and measures proposal.

The results of the daylight optimization and design recommendations are discussed and presented in Chapter 8 and Appendix IV, section D (González Matterson and Salom 2015).

3.4.1.1 Dynamic lighting simulations

Dynamic simulations were carried out to assess the performance of different skylight glazing solutions with the incorporation of diffusers/baffles, according to the optimization goals. Different scenarios were simulated by DAYSIM software (NRC- ISE 2012, Version Beta 3.1). The results expected to find the best skylight solution, in terms of the following objectives:

- To accomplish and verify a good level of horizontal illuminance in the court: Daylight Factor-DF%, Daylight Autonomy-DA% (annual base)
- To verify and achieve a minimum uniformity – U of horizontal illuminance on the court, to perform training and competition sports activities: E_h training > 200 – 300 lx, and if possible E_h competition> 300 – 500 lx up to 1000 lx, depending on the sport and TV broadcasting conditions
- To avoid direct light, sunlight and sun spots on the court surface by the toplighting system

To minimize or prevent glare situations in the court by the toplighting system, through simplified DGP% (Wienold and Christoffersen 2006).

An orthogonal grid (+1.00m) with sensors regularly spacing in the court area (x=5.0, y=5.0m) with 2,600m^2 of surface was set to measure and display the obtained values. The occupancy schedule was set according to sports halls opening times, with a lighting level E_h = 300 lx corresponding to training conditions.

Simulation models

Simplified 3D models or scenarios were built in SKETCHUP software (Google 2010, Version 8.0.11752, 2010) and simulated by DAYSIM software (NRC- ISE 2012, Version Beta 3.1) to find the best solution for the skylight shape and glazing surface. The contribution of natural light from windows was not included in the simplified models. The expected results were expressed in DF%, DA%, DA_{MAX}% and DGP%.

DGP% calculations

For the Daylight Glare Probability - DGP% calculations from a user viewpoint was set in the centre of the court (+1,55) with 2 two main view directions: towards the South and North, to evaluate the efficacy of the vertical baffles implementation and materialization of the skylight.

3.4.1.2 Daylighting design recommendations

Based on the previous assessments of graphic and design project documentation and simulations results, daylighting design strategies and specific measures were proposed to the design team to be included in the project design of the Palau d'Esports Catalunya-PEC, see Chapter 8.

3.4.2 Post Occupancy Evaluation - POE

After the Palau d'Esports Catalunya-PEC (Catalonia Sports Palace) was built for the 2018 Mediterranean Games, two monitoring campaigns or Post-Occupancy Evaluation-POE were carried out.

The POE evaluation was performed to obtain objective and subjective data about the achievement of the objectives related to the nZEB and the daylight optimization of the skylight. The study was composed of two different phases of measurements, according to the following:

- 1st monitoring campaign of POE
- 2nd monitoring campaign of POE

The 1st monitoring campaign was focused on the visual comfort assessment by in-situ measurements to verify if the initial design goals of the daylight optimization were achieved.

The 2nd campaign was focused on the thermal comfort, the air quality and environmental survey evaluation, including the visual comfort and TV broadcasting conditions during the international competitions.

The results of the implementation of skylight optimization with design recommendations and the monitoring campaign are discussed and presented in Chapter 8 and Appendix IV, section C1 (González Matterson, Salom and Ortiz 2017; Ortiz et al. 2019).

3.4.2.1 1st campaign of POE: in-situ measurements

The visual comfort monitoring campaign was focused on a detailed assessment of the athlete and spectator users under daylight conditions by lighting quantity and quality evaluation. These measurements were carried out in the last phase of the construction works of the Palau d'Esports de Catalunya-PEC, according to the following procedures:

- Eh horizontal illuminance
- HDRI survey

The methodology used to assess the visual comfort was based in horizontal illuminance - E_h measurements (+1,10m) and the acquisition of High Dynamic Range Images - HDRI from user's viewpoints, as described in section 3.2, by luminance camera or Charged Couple Device – CCD, see Figure 3-29.

Eh horizontal illuminance

The horizontal illuminance measurements were made with an orthogonal grid of 1,920m^2 in the playing area at +1,10m, see Figure 3-28.

The total exterior horizontal illuminance E_h was registered at the same time than E_h at indoors, and without obstructions on the roof of the building.

HDRI survey

The HDR images were taken by video photometer LMK 98-40 and digital reflex camera Nikon D-60 at +1.55 level, to cover the athletes and spectators/TV broadcasting visual field of view - FOV.

For the potential glare source assessment, three 3 regions of interest were established in the Field of View – FOV (Inanici 2005b), see Figure 3-8.

The average luminance values of each region were calculated and luminance thresholds were identified for each image with the LMK Laboratory software (TechnoTeam 2015, Version 15.6.23). The threshold was calculated multiplying the average luminance value of the image by factor 7, according to Findglare (Ward 1993). The resulting HDR images are displayed with False Colour Analysis with luminance – L values, see Figure 3-29.

3.4.2.2 2nd campaign of POE: spectators visual comfort survey

The second campaign was carried out during the realization of the 2018 Tarragona Mediterranean Games and focused on thermal comfort and air quality. Measurements were complemented with environmental comfort questionnaires, including visual comfort (Ortiz et al. 2019).

The objective of the environmental survey was to compare the measured parameters with the perception of users by an environmental survey, see Table 3-7.

Comfort	Question
Visual	How do you perceive the illumination level?
Thermal	Which of the following options best indicate your clothing?
	How do you asses your thermal sensation?
	How do you perceive the humidity level?
	How do you perceive the air movement?
Air quality	How do you perceive the air (polluted/fresh)?

Table 3-7. Table with questions of environmental survey.

During the 2018 Mediterranean Games, the spectators were requested to fill an environmental questionnaire with closed-ended responses. Among others, they were asked about how they perceived the lighting level of the court and 5no. rating options are given: very weak, slightly weak, neutral, slightly intense and very intense, see Chapter 8.

3.5 Chapter conclusions

Objective and subjective information was required to demonstrate the main hypothesis, considering the performance of daylighting and its contribution to the visual requirements and visual comfort of users in existing sports halls.

Taking into account that there are no specific procedures to assess the indoor visual comfort in day-lit sports halls, a methodology was designed and implemented with a comprehensive approach. The methodology was developed in three main parts, containing an array of techniques and procedures to evaluate quantitative and qualitative parameters. The completion of each part presented different levels of complexity, due to process and instrumentation and supported by consolidated and experimental procedures. In this sense, this study offered a better understanding about which metrics and parameters are significant to be evaluated in sports halls as type of buildings.

Measurements

Despite the difficulty of the data acquisition in in-use buildings, the in-situ measurements were useful to get objective information about daylighting performance in existing sports halls buildings.

Site visits: subjective assessment

The site visits allowed to identify main issues to maintain the visual comfort in existing sports halls by subjective assessment of case studies and samples selection. These subjective observations were helpful to design the methodology, considering the hypothesis formulated.

HDR survey: users' visual comfort by Field of View - FOV

The assessment of the visual task, during sports activities and performed by dynamic users, required of simplifications to capture the 360° luminous environment and the field of view - FOV of athletes and spectators.

Multi view-directions and user's positions or viewpoints into the space were established to effectively evaluate visual comfort.

Accordingly, to simplify the assessment and to explore different visual requirements of users, two main groups were identified:

- Athletes: dynamic position and visual task
- Spectators/remote spectators and TV broadcasting: static position and dynamic visual task

The HDR technique was implemented for luminance data acquisition in the visual field. This technique allowed the use of post processing tools as calibration, False Colour Images, glare analysis and obtaining luminance distribution patterns.

Numerical simulations

Daylight static and dynamic simulations were proposed to study and optimize different alternatives and scenarios, by virtual or real scale models. Photorealistic rendering simulations were useful to display images containing different passive and active measures for tests realization and subjective evaluation. This also helped in the decision-making process, offering the possibility to test different variables, based on the objectives of the optimization.

Moreover, simulations allowed the enhancement of in-situ data acquisition and to calibrate models based on real performance.

Experimental test

The experimental test was designed to evaluate the effectiveness of daylighting strategies and measures, proposed with the aim to improve visual conditions. Throughout this evaluation by participants, the proposed strategies and measures could be validated or not. Besides, simulations proved to be an advantageous tool to test, evaluate and optimize a number of design strategies and measures. This can be useful either before the measures implementation in existing sports halls or during the building design and optimization process of a new one.

The surveys included open-ended and closed-ended questions, that were collected from users during the tests realization. Most of them were open-ended questions because allowing participants to respond in a more spontaneous way, avoiding potential bias from the researcher. They produced a more diverse and rich array of responses, although it leads to a high level of difficulty to classify and organize results.

Qualitative analysis of user responses

The qualitative evaluation of survey data offered rich information about users' preferences. However, the transcripts, classification and identification of key topics from open-closed responses resulted in a complex and time-consuming process.

Finally, all the information obtained resulted valuable as a contribution of real data from sports halls, pondering the impact of the daylighting design strategies by users and their subjective perception.

The survey data collected from sports' users both in laboratory and real conditions was a valuable outcome of this research, regarding the visual preferences and comfort under natural light.

4

Case studies

The previous chapter describes the methodology designed and proposed for this research. Accordingly, existing sports halls were assessed as case studies to obtain real data, concerning the performance of daylighting systems and visual comfort.

This chapter describes the case studies selected in Catalunya for the reference and the final samples, including Olympic buildings from the Barcelona 1992 Olympics Games, and users of these sports facilities. The architectonic description of buildings selected consist of daylighting design strategies, toplighting and sidelighting systems, solar protection devices and indoor surfaces, including material properties and colours.

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4.1. Case studies: top-lit sports halls buildings

After the organization of the Olympic Games in Barcelona 1992 and the realization of a comprehensive urban rehabilitation plan and sports facilities, good examples are in-use today of day-lit and top-lit triple pavilions and sports palaces.

The luminous architectural environment in sports halls buildings, as a specific type of building, defines the perception of the building's users, as athletes, spectators, and broadcasting television - remote viewers.

The selected case studies to study the performance of daylight systems in sports hall buildings are the multisport halls or triple pavilions PAV-3, according to the Consell Catlatà de l'Esport-CCE technical datasheet (Generalitat de Catalunya 2005b) and located in Catalunya. The triple pavilion or PAV-3 typology was selected because there is mixture of these users, according to the hypothesis and objectives of this work.

4.1.1. The Barcelona 1992 Olympic Games

The Games of the XXV Olympiad Barcelona 1992- Barcelona'92, were held from 25th of July to 9th of August and were organized by the Barcelona'92 Olympic Organising Committee-COOB'92.

The Master Plan of the Games was organized in programmes and included a series of town-planning works in Barcelona, which had been postponed for many years. The development of the Parc de Montjuïc, the recovery of the beaches and sea front, the reform of four Olympic areas, the construction of ring roads, the new sports facilities and large-scale telecommunication works, were the main actions carried out thanks to the Games (COOB'92 S.A. 1992).

The criteria for the management of the facilities aimed to maintain the balance between a concentrated organization in the territory and a dispersion of elements in the region of Catalonia, see Figure 4-1 and Figure 4-2. For that, nine areas composed the Olympic system:

- Montjuïc
- Diagonal: including renovated Palau Blaugrana (judo, roller hockey and taekwondo)
- Parc du Mar
- Vall d' Hebron: with the new Vall d' Hebron pavilion (volleyball), see Figure 4-6
- Poble nou
- Prat de Llobregat
- Badalona
- Banyoles

The Montjuïc area was the main site of the sports facilities, that included the Olympic Ring and, among others: the renovation of the Estadi Olympic de Montjuïc (athletics and opening/closing ceremonies), see Figure 4-3 and Figure 4-4, and the new following buildings:

- Palau Sant Jordi (gymnastics), see Figure 4-5 and Figure 4-7.
- INEFC building (wrestling), see Figure 4-5 and Figure 4-7.
- L'Espanya Industrial Pavilion (weightlifting)

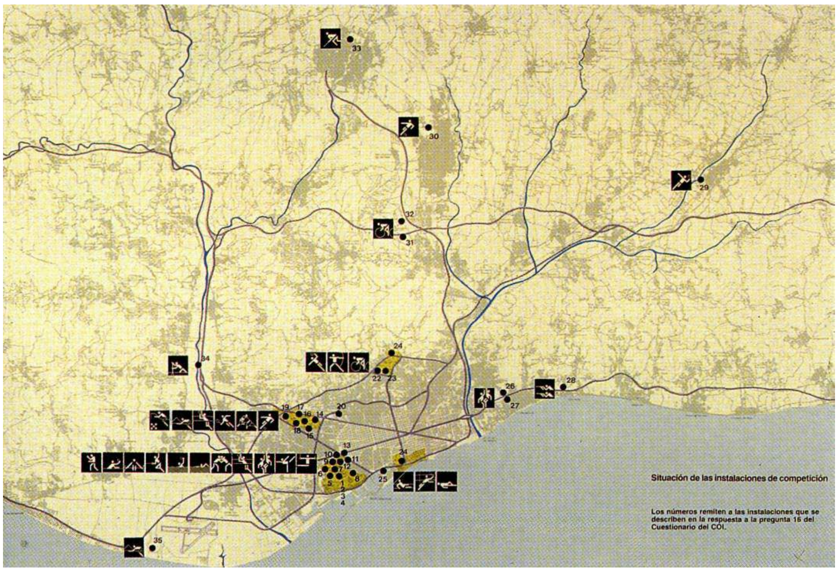


Figure 4-1. Map showing the Olympic venues in the city for the Barcelona 1992 Candidature Dossier (Source: COOB'92 S.A 1992, pp.270).

Figure 4-2. Plan with the main four Olympic clusters in Barcelona city for the 1992 Olympic Games (Source: GN Institut Geogràfic Nacional, cited in Pala 2017[1]).

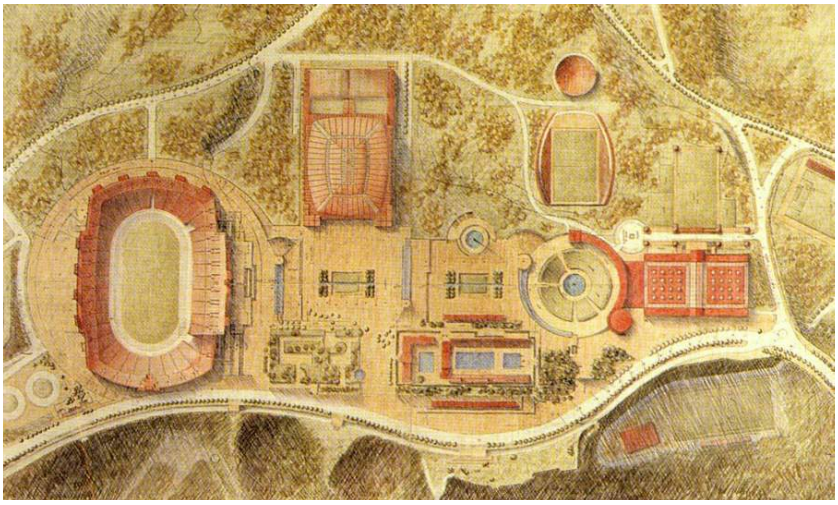


Figure 4-3. Drawing of the Barcelona Olympic Games proposal containing the Olympic ring in Montjuïc area: the rehabilitation of the Ancient Olympic stadium and two new indoors facilities (Source: COOB'92 S.A 1992, pp. 229).

[1] Barcelona '92, molt més que uns Jocs. https://www.catalan-architects.com/ca/architecture-news/destacats/barcelona-92-molt-mes-que-uns-jocs

Also, there were subsites in the territory of Catalunya to celebrate competitions. For example, the new sport facilities: the Palau d'Esports de Badalona (basketball) and the Palau d'Esports Granollers (handball), see Figure 4-6 and Figure 4-7.

The sport's highlights of Barcelona'92 were that basketball debuted as full medal discipline, having appeared as exhibition at six previous Games. Also, badminton and woman's judo were added to the Olympic program (Olympic.org 2019).

The renewal, improvement and expansion of sports facilities for the Olympic Games were also accompanied by the realization of a comprehensive global urban plan, including: housing and transport infrastructure and the recovery of metropolitan degraded areas. After the Games, Barcelona was completely transformed in a new century city (Barbieri 1999).

4.1.2. Triple pavilion PAV-3

The layout of the building is organized around the central court or playing area, with seating area in one side and the support facilities in the opposite, see Figure 4-8. Also, in some cases, with high spectator capacity, the seating area is positioned around the four sides of the court.

The playing area is suitable for the practice of sports such as badminton, volleyball, basketball, physical education, and complementary activities, see Moreover, official competitions can be held with optimal visibility from the seating area in the longitudinal sense. Also, it allows the sub-division of three tracks in parallel (cross wise sense) for training and competitions level of play. The main futures of this building type are:

- large and deep floor plan
- skylights and windows to day lit the court
- no standard materialization of the daylighting systems and interior space, apart from the layout and court dimensions

The court or playing area is designed to be the main space of the building and organized with the possibility to divide in 3 a-side pitches by internal divisions as rolled blinds, allowing the simultaneously use if it is required, see Figure 4-10. This pavilion module is around 2.500m^2 surface with a court or playing area with 45m x 27m 1215m^2, with variable capacity for seating spectators.

4.1.3. Users of the triple pavilion PAV-3

The users of this multipurpose sports hall in Catalonia are the schoolkids 41%, followed by the elite athletes 39%, and the general public with 20%, according with the athletes' subgroups established. Moreover, in terms of the intensity of use of this pavilion PAV-3 by athletes (weekdays), the graphic shows that the peak hours occur during daytime: in the morning at 10,00 am, and in the afternoon at 3,00 and 4,00 pm, with 60 uses per hour, but with a pronounced drop at noon, probably due to lunchtime, see Figure 4-9. This trend is also maintained in the rest of pavilion types with inferior values (Generalitat de Catalunya 2005a, pp. 190).

Figure 4-4. Image of the Olympic Stadium on the inauguration of the XXV Barcelona Olympic Games on 25th of July in 1992 (Source: Fundació Barcelona Olimpica[2]).

Figure 4-5. Images of the Olympics venues built for and during the 1992 Barcelona Olympics Games, in the Montjüic area.

The Institut Nacional d'Educació Física de Catalunya - INEFC building, left, and Palau Sant Jordi, right. (Source: Fundació Barcelona Olimpica[3]).

Figure 4-6. Images of the Olympics venues built for and during the 1992 Barcelona Olympics Games.

Vall d'Hebron Pavillon (volleyball), left, and Espanya Industrial (weightlifting), right (Source: Fundació Barcelona Olimpica[2]).

Figure 4-7. Images of the Olympic venues built for the 1992 Barcelona Games after the Games (2009).

The INEFC, left, Palau Sant Jordi- PSJ, centre, and Palau d'Esports de Granollers - PEG, right.

[2] http://www.fundaciobarcelonaolimpica.es/index.asp

[3] 25è aniversari dels Jocs Olímpics i Paralímpics BCN '92. http://lameva.barcelona.cat/25anysolimpica/ca/seus-92

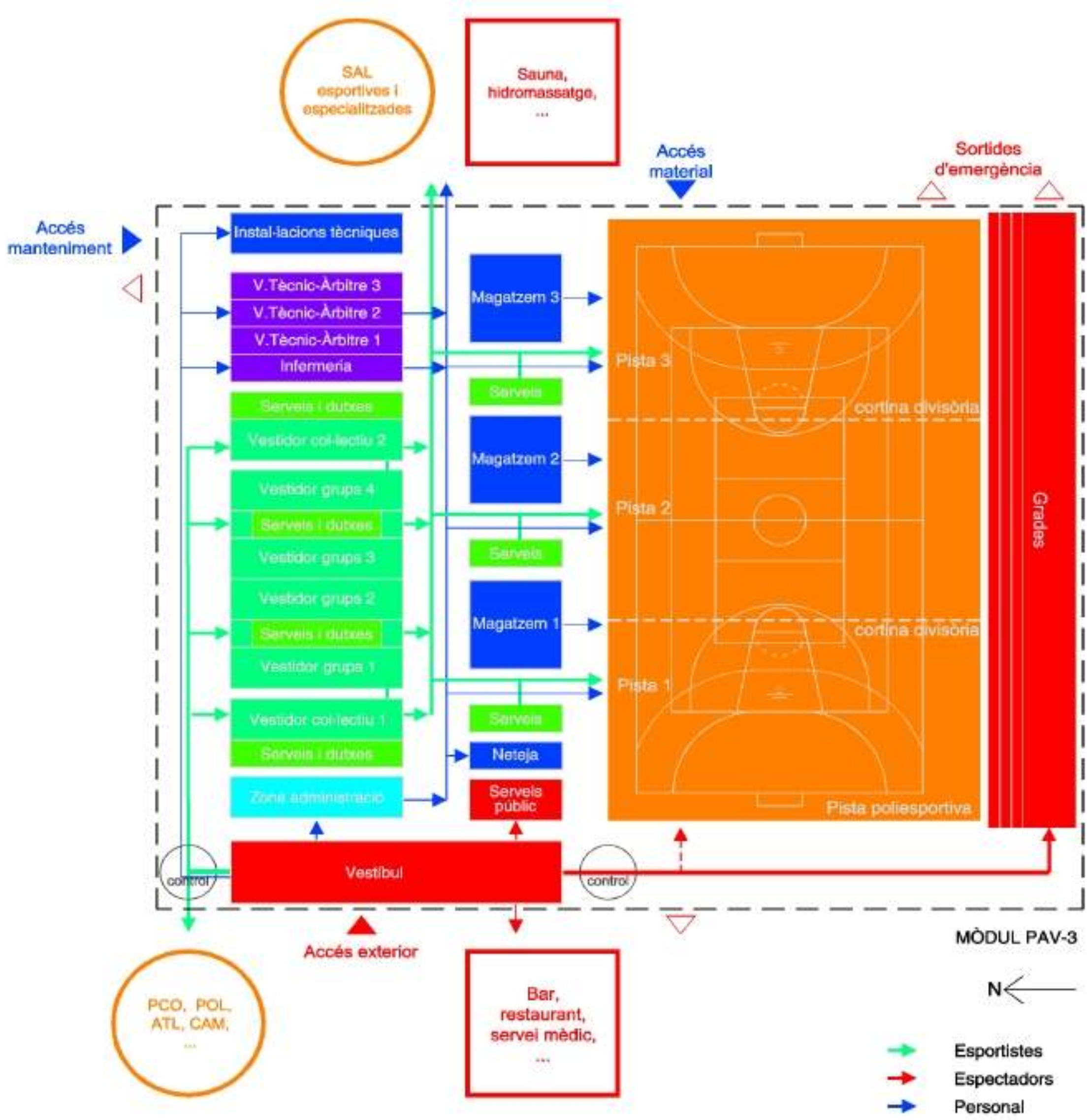


Figure 4-8.Graphic showing the functional layout organization of the Multipurpose sports halls, triple pavilion PAV-3 in Catalonia, with surfaces and relations with the playing area according to users, according to Technical datasheet (Source: Generalitat de Catalunya, 2005b, pp.4).

Colors: orange for the court or playing area, green for athletes, red for spectators, blue for the facility management and staff and purple for judges and infirmary.

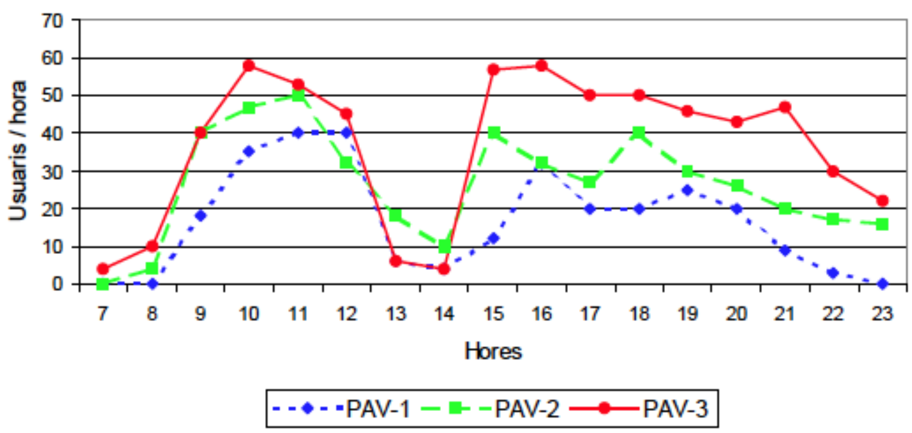


Figure 4-9. Graphic showing the mean values of number of uses per hour (vertical axis) by the athlete users (weekdays) or utilization level in types of pavilions in Catalonia (Source: Generalitat de Catalunya, 2005a, PIEC, pp. 190)

The triple pavilion- PAV-3, corresponds to the multipurpose sports halls selected for this study.

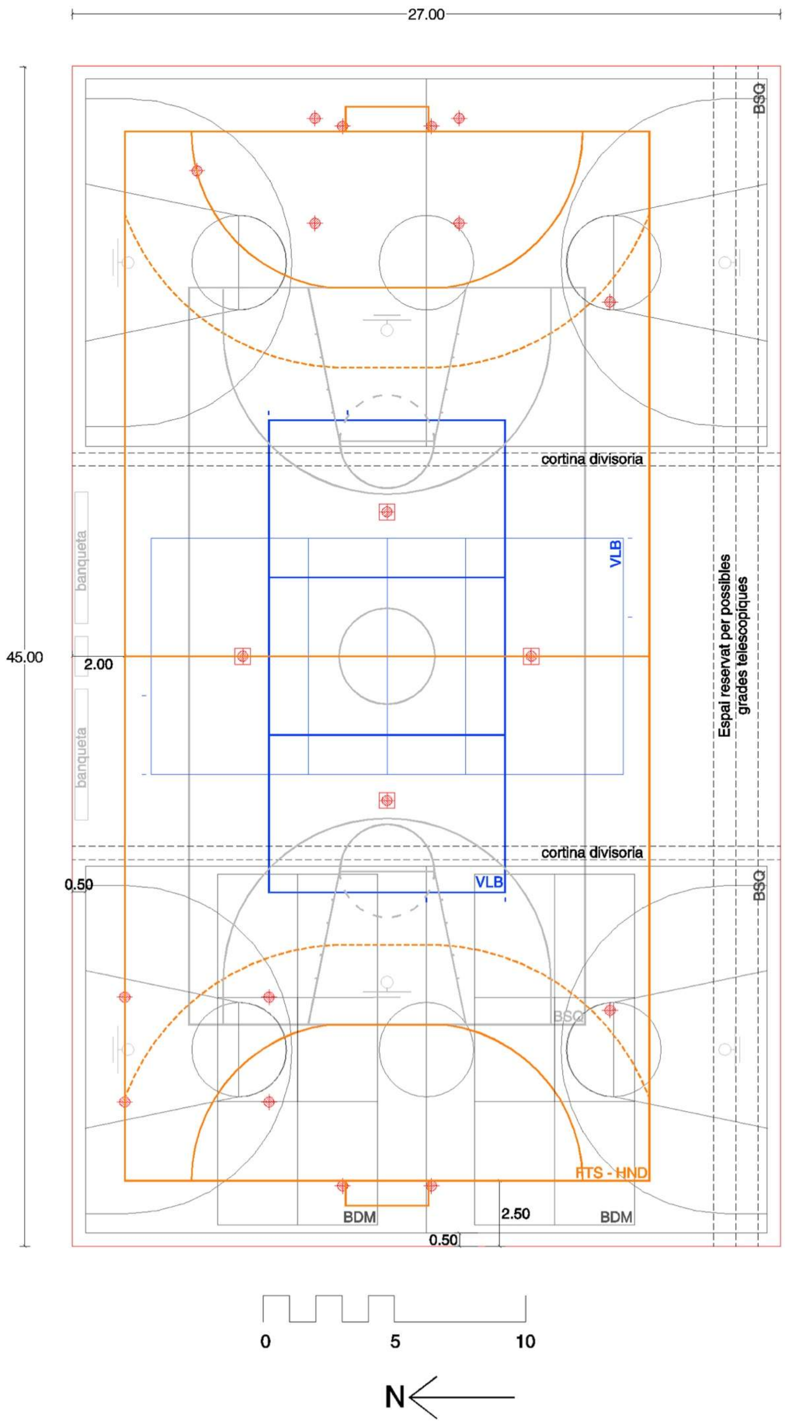


Figure 4-10. Scheme of the court of the triple pavilion PAV-3, according to the Consell Català de l'Esport – CCE (Source: Generalitat de Catalunya, 2005b, pp.4)

The court area of the standardized PAV-3 is 45m x 27m, with different sports delimitations:

BSQ: Basketball (grey), VLB: Volleyball (blue), FTS: Five-a-side Football and HND: Handball (orange), BDM: Badminton (dark grey).

The dash line on the right, represents the reserved space for the possible addition of telescopic tribunes.

4.2. Reference sample

The case studies of the reference sample were selected among triple pavilion PAV-3 type of multipurpose sports halls, according to the following selection criteria:

- if the sports hall has daylighting systems, sidelighting and toplighting
- if the toplighting is the main daylighting system
- if it is located in Barcelona and surroundings
- if it is accessible to data collection to perform a visual comfort basic assessment, including: site visits, photo surveys, spots measurements and interviews.

According to the selection requirements, 13no. sports halls buildings were selected to perform a basic assessment, as shown in Figure 4-11. The buildings selected are mainly located in Barcelona, including subsites in the territory of Catalunya to celebrate competitions of the 1992 Olympic Games (see Chapter 2), as Granollers, Girona and Banyoles, see location in Figure 4-12 and listed as follows:

- Centre Esportiu Municipal L'Espanya Industrial - CEM EI, Barcelona
- Centre Esportiu Municipal La Verneda- CEM LV, Barcelona
- Centre Esportiu Municipal Vall d'Hebron - CEM VH, Barcelona
- Centre Esportiu Municipal del Raval Can Ricart - CEM RCR, Barcelona
- Complex Esportiu del Consell Català de l'Esport- CE CCE, Esplugues de Llobregat
- Institut Nacional d'Educació Física de Catalunya Montjuïc – INEFC, Barcelona
- Palau Blaugrana Futbol Club Barcelona- PBFCB, Barcelona
- Palau Municipal d'Esports de Badalona -PMEB, Badalona
- Palau Sant Jordi - PSJ, Barcelona
- Palau d'Esports de Granollers –PEG, Granollers
- Pavelló Poliesportiu Municipal de Banyoles - PPMB, Banyoles
- Pavelló Municipal de Girona Fontajau - PMGF, Girona
- Poliesportiu Municipal Virrei Amat - PMVA, Barcelona

According to the methodology proposed, see previous Chapter 3, information about the site visits, photographic survey carried out and the conditions of the subjective assessment was gathered and expressed in the following format:

- Date: Day/Month/Year
- Time: expressed in Central European Time- CET or UTC/GMT +1h in winter, Central European Summer Time- CEST a or UTC/GMT +2h in summer, according with the Daylight-Saving Time
- Sky conditions: clear, overcast, intermediate with clouds
- Artificial lighting: if it is on



CEM L'Espanya Industrial	**CEM La Verneda**	**CEM Olímpics Vall d'Hebron**
CEM EI	**CEM LV**	**CEM VH**
(R. Artigas & R. Sanabria)	(M. Perez de Arenaza)	(J. Garcés & E. Sória)
1991	1987	1991



CEM del Raval Can Ricart	**Complex Esportiu del Consell Català de l'Esport**	**Institut Nacional d'Educació Física de Catalunya Montjuïc**
CEM RCR	**CE CCE**	**INEFC M**
(P. Buil & J. Fornells)	(R. Balcells)	(R. Bofill)
1989, 2006	1992	1990



Palau Blaugrana FC Barcelona	**Palau Municipal d'Esports de Badalona**	**Palau Sant Jordi**
PBFCB	**PMEB**	**PSJ**
(J.Soteras & F. Cavaller)	(E. Bonell, F. Rius & J.M. Gil)	(A. Isozaki & M. Kawaguchi)
1972	1991	1991




Palau d'Esports de Granollers	**Pavelló Poliesportiu Municipal de Banyoles**	**Pavelló Municipal de Girona Fontajau**	**Poliesportiu Municipal Virrei Amat**
PEG	**PPMB**	**PMGF**	**PVA**
(P. Bonet)	(E. Bonell & J. M. Gil)	(E. Bonell & J. M. Gil)	(M. Brullet)
1991	1992	1993	1987

Figure 4-11.Images showing the court of the selected case studies for the reference sample, design architect and year of built.

The features of the reference sample buildings listed above, are summarized in Table 4-1 and Table 4-2, that contain information about: coordinates location, reference code, address, owner, management, dimensions and surface of the court, spectator capacity, type of athletes/ users, and daylighting systems. The table was elaborated from data collected from the site visits, as well as with information obtained from the Sports facilities census (Generalitat de Catalunya 2014), elaborated by the Consell Català de l'Esport- CCE, Servei d'Equipaments Esportius.

The toplighting systems are the main source of natural light in all buildings considered for the reference sample, with the exception of the PBFCB (clerestory).

4.2.1. Luminous space

The luminous space, defined by the court and the surroundings, has diverse materiality, see Figure 4-11., in terms of daylight systems and interior architecture.

The main features of toplighting and sidelighting systems of the court in the reference sample are summarised and presented in Table 4-4. It includes the characteristics of main daylight systems, control and shading devices, and the internal architectonic surfaces properties, in terms of reflectance and colours, from a subjective evaluation, obtained from the first site visits, interviews and photographic survey.

4.2.2. Daylighting systems

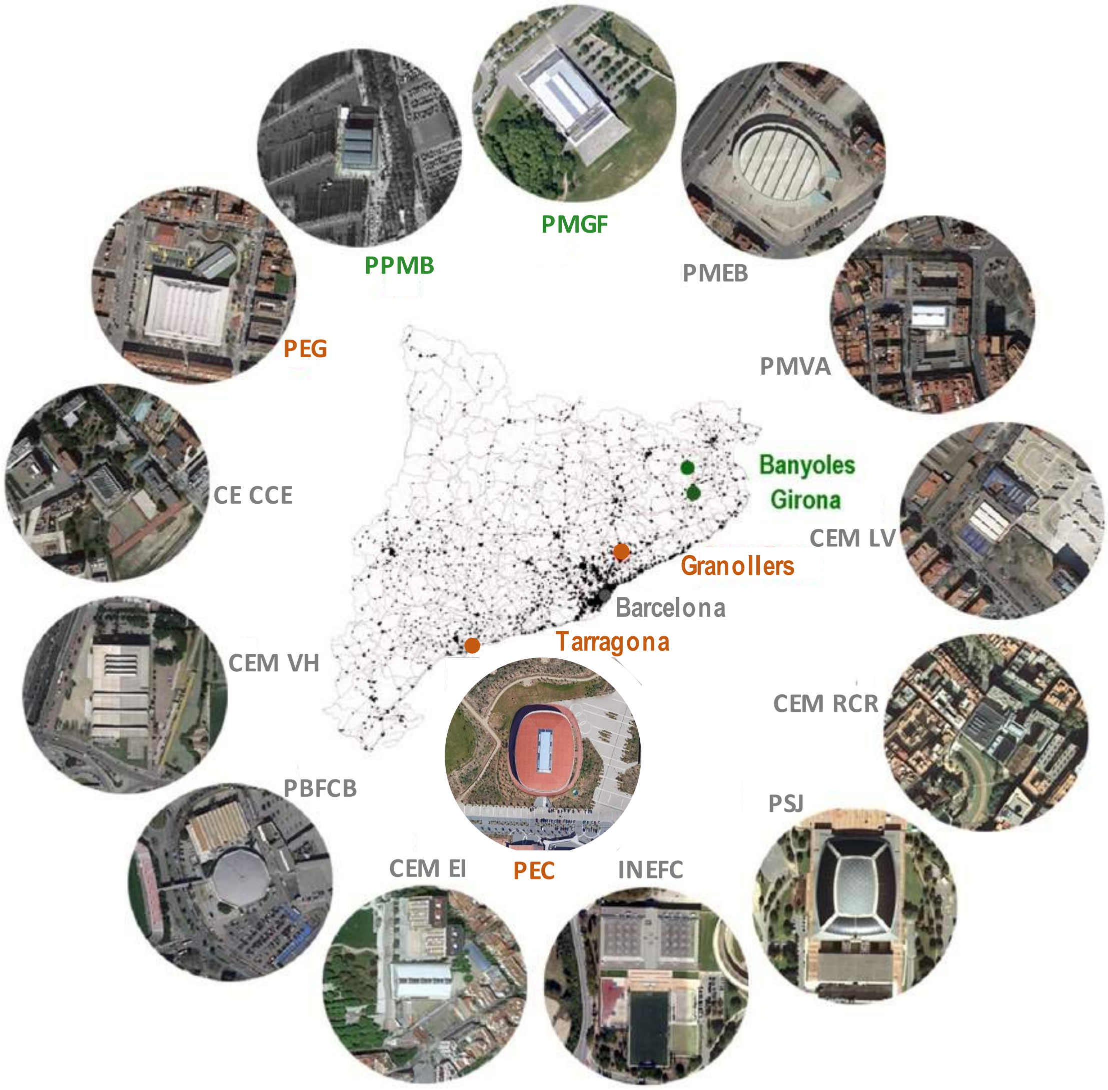
The use of daylight systems has been verified in the reference sample, in the same conditions of use as they were designed.

According to the site visits carried out, in most of cases, the daylit systems were providing minimum daylight conditions for sports activities, without artificial light. However, in the PPMB building, after the realization of the 1992 Olympic Games, the sawtooth was totally shuttered-down due to artificial lighting requirements in competition conditions.

Most of case studies, 7no. sport halls, have skylights and 2no. monitor roofs, followed by 4no. with sawtooth as main toplighting systems.

The majority of buildings have bilateral and multilateral windows as main sidelighting system, according to the following, see Figure 4-11.:

- Windows covering all the side walls/back walls: CEM VH and CEM RCR (entrance wall)
- Windows covering lower and middle part of side walls: CE CCE, PPMB, and CEM RCR
- Windows covering the middle and upper part of side walls: CEM LV, CEM VH, INEFC M, PPMB buildings
- Windows covering the upper part of side walls: CEM EI, CEM LV, PBFCB, PSJ, PEMVA and PEG

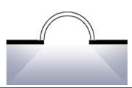
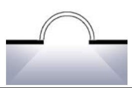
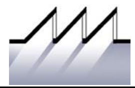
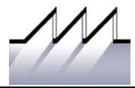
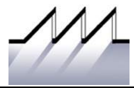
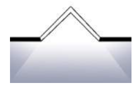


- **CEM EI**, Barcelona
  Centre Esportiu Municipal L'Espanya Industrial
- **CEM LV**, Barcelona
  Centre Esportiu Municipal La Verneda
- **CEM VH**, Barcelona
  Centre Esportiu Municipal Vall d'Hebron
- **CEM RCR**, Barcelona
  Centre Esportiu Municipal del Raval Can Ricart
- **CE CCE**, Esplugues de Llobregat
  Complex Esportiu del Consell Català de l'Esport
- **INEFC**, Barcelona
  Institut Nacional d'Educació Física de Catalunya Montjuïc
- **PBFCB**, Barcelona
  Palau Blaugrana Futbol Club Barcelona
- **PMEB,** Badalona
  Palau Municipal d'Esports de Badalona
- **PSJ**, Barcelona
  Palau Sant Jordi
- **PMVA**, Barcelona
  Poliesportiu Municipal Virrei Amat
- **PEG**, Granollers
  Palau d'Esports de Granollers
- **PMGF**, Girona
  Pavelló Municipal de Girona Fontajau
- **PPMB**, Banyoles
  Pavelló Poliesportiu Municipal de Banyoles
- **PEC**, Tarragona
  Palau d'Esports Catalunya (new building)

Figure 4-12. Map containing the sports facilities in Catalunya[4] with location and satellite roof view[5] of the sports halls selected for the reference and final sample, and the new Palau d' Esports Catalunya.

The map contains Olympic buildings of the 1992 Olympic Games, including subsites in the territory of Catalunya to celebrate competitions.

[4] (Source: Generalitat de Catalunya 2005a, cover)
[5] (Source: ©Google Maps)

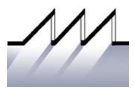
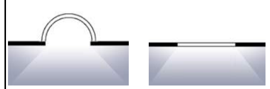
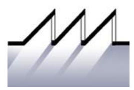
Sports hall	Centre Esportiu Municipal L'Espanya Industrial	Centre Esportiu Municipal La Verneda	Centre Esportiu Municipal Olímpics Vall d'Hebron	Centre Esportiu Municipal del Raval Can Ricart	Complex Esportiu del Consell Català de l'Esport	Institut Nacional d'Educació Física de Catalunya Montjuïc	Palau Blaugrana Futbol Club Barcelona
Acronym	**CEM EI**	**CEM LV**	**CEM VH**	**CEM CRC**	**CE CCE**	**INEFC**	**PBFCB**
Geographical coordinates	41°22'39.3"N 2°08'32.8"E	41°25'31.2"N 2°12'16.5"E	41°25'40.1"N 2°08'42.8"E	41°22'38.5"N 2°10'15.0"E	41°22'44.2"N 2°05'43.6"E	41°21'55.7"N 2°08'51.8"E	41°22'48.0"N 2°07'12.8"E
Reference number (CEEC) [1]	0801930988	0801930621	0801930954	0801930325	0807710042	0801930422	0801931022
Address	Parc de l'Espanya Industrial, s/n 08014 Barcelona	C. Binèfar, 10-14 08020 Barcelona	Pg. Vall Hebron, 166-176 08035 Barcelona	C. St. Oleguer, 10 08001 Barcelona	C. Sant Mateu, 27-37 08950 Esplugues de Llobregat	Av. de l'Estadi, 12-22 08038 Barcelona	C. Arístides Maillol, 12-18 08028 Barcelona
Owner	Ajuntament de Barcelona	Ajuntament de Barcelona	Ajuntament de Barcelona	Ajuntament de Barcelona	Consell Català de l'Esport	Generalitat de Catalunya	Futbol Club Barcelona
Management	Secretariat d'Entitats de Sants, Hostafrancs i La Bordeta	Associacio Sant Martí Esport	Ige BCN SL	Club Lleuresport	Consell Català de l'Esport	Institut Nacional d'Educació Física de Catalunya	Futbol Club Barcelona
Athletes users	AU1	AU1	AU1	Scholars, general public.	Scholars, elite athletes	AU1	Elite athletes
Spectators capacity	400 seats	528 seats	4.068 seats	-	220 seats	-	7.500 seats
Court dimensions	48,0 m x 32,5 m	45,0 m x 27,0 m	51,7 m x 32,7 m	45,0 m x 27,0 m	43,7 m x 31,6 m	48,0 m x 48,0 m	40,0 m x 20,0 m
Surface (m^2)	1.235,0	1.215,0	1.690,5	1.215,00	1.380,9	2.304,0	800,0
Pavement	Wood, elastic	Wood, elastic	Synthetic, rigid	Synthetic, rigid	Wood, elastic	Wood, elastic	Wood, rigid
Sports	S3	S1+ skating	S1 + volleyball	Multisport activities	S2 + Badminton	Multisport activities	Multisport activities
Daylighting features							
Roof light configurations	Lineal half barrel roof-light (East-West axis)	2 lineal barrel roof lights (NW –SE axis)	4 North monitor roof	4 North-east monitor roof	North saw tooth roof	16 Pyramid roof lights + vertical wells	-
Side lighting	Bilateral clerestories + light shelves (North, South)	Unilateral windows (SW)	Bilateral windows (West, East)	Multilateral windows (NW, SW, NE)	Bilateral windows (NE, SW)	Unilateral windows (West)	8 Multilateral clerestories (NW, SW, SE, NE)

Athletes users: A1= scholars, elite athletes, general public.
Sports: S1= Basketball, 5 or 7 a-side Football, Handball; S2= Basketball, 5 or 7 a-side Football, Handball, Volleyball; S3= Basketball, Handball, Volleyball, Fencing.

[1] Cens d'Equipament Esportius de Catalunya- CEEC (2014, Generalitat de Catalunya). Consell Català de l'Esport, Servei d'Equipaments Esportius.

Table 4-1. Main features and geographical coordinates [*] *of the reference sample (part 1/2): CEM EI, CEM LV, CEM VH, CEM CRC, CE CCE, INEFC and PBFCB buildings.*

[*] (Source: ©Google maps)

Sports hall	Palau Municipal d'Esports de Badalona	Palau Sant Jordi	Palau d'Esports de Granollers	Pavelló Poliesportiu Municipal de Banyoles	Pavelló Municipal de Girona Fontajau	Poliesportiu Municipal Virrei Amat
Acronym	**PMEB**	**PSJ**	**PEG**	**PPMB**	**PMGF**	**PMVA**
Geographical coordinates	41°26'33.7"N 2°13'56.6"E	41°21'48.8"N 2°09'10.8"E	41°35'53.9"N 2°17'16.4"E	42°07'35.0"N 2°45'44.0"E	41°59'27.8"N 2°48'38.6"E	41°25'47.0"N 2°10'26.5"E
Reference number (CEEC)[2]	0801550141	0801930836	0809610052	1701570007	1707920081	0801930846
Address	C. Ponent, 143-161 08912 Badalona	Pg. Olímpic, 5-7 08038 Barcelona	C. Francesc Macià, s/n 08401 Granollers	Parc de la Draga 17820 Banyoles	Av. Josep Tarradelles, 22-24 17005 Girona	C. Joan Alcover, 6 08031 Barcelona
Owner	Ajuntament de Badalona	Ajuntament de Barcelona	Ajuntament de Granollers	Generalitat de Catalunya	Ajuntament de Girona	Ajuntament de Barcelona
Management	Club Joventut de Badalona	Barcelona Serveis Municipals S.A.	Ajuntament de Granollers	Ajuntament de Banyoles	Ajuntament de Girona	S.E.S.E. Seccio Esportiva Santa Eulalia
Athletes users	Scholars, elite athletes	Elite athletes	AU1	Elite athletes	Elite athletes, general public.	AU1
Spectators capacity	12.500 seats	14.950 seats	5.800 seats	461 seats	5.070 seats	225 seats
Court dimensions	46,0 m x 24,0 m	97,0 m x 37,0 m	49,80 m x 30,70 m	45,0 m x 280,0 m	33,1 m x 19,8 m	44,8 m x 25,0 m
Surface (m^2)	1.104,0	4.500,0	1.528,9	1.260,0	655,4	1120,0
Pavement	Wood, elastic	Concrete	Synthetic, rigid	Wood, rigid	Wood, rigid	Wood, elastic
Sports	Basketball	Multisport activities	Handball	Basketball	Basketball	Basketball
Daylighting features						
Roof light configurations	North-West Sawtooth roof	Dome roof lights + 8 flat roof lights	7 Tilted lineal roof-lights (NE –SW axis)	North Sawtooth roof	NE- SW Monitor roof	Lineal half barrel roof-light (East-West axis)
Side lighting	-	Multilateral windows (North, East, South, West)	Bilateral windows (West- East)	Bilateral windows (West, East)	Multilateral windows (NE, SE, SW, NW)	Bilateral windows (North, South)

Athletes users: AU1= scholars, elite athletes, general public.
Sports: S1= Basketball, 5 or 7 a-side Football, Handball; S2= Basketball, 5 or 7 a-side Football, Handball, Volleyball;

[2] Cens d'Equipament Esportius de Catalunya- CEEC (2014, Generalitat de Catalunya). Consell Català de l'Esport, Servei d'Equipaments Esportius

Table 4-2 . Main features and geographical coordinates[*] of the reference sample (part 2/2): PMEB, PSJ, PEG, PPMB, PMGF and PMVA buildings.

[*](Source: ©Google maps)

4.2.3. Daylight control and shading devices

Regarding the control of natural light and shading devices, notes were taken about the existence of devices and its current operation, as following:

- Toplighting: there are fixed devices for daylight control as splayed surfaces in the ceiling, screens, louvers and baffles in the CE CCE, CEM CRC, CEM EI, CEM VA, and PEG buildings, see Figure 4-13. However, there is a lack of mobile shading devices and black out in the majority of case studies.
- Sidelighting: there is a lack of movable shading devices in windows, with the exception of blinds for black out in the CEM VH, CEM CR buildings, see Figure 4-14. Also, there are fixed louvers in middle windows and light shelves in upper windows in the CEM VH and CEM EI buildings, respectively.

Moreover, the permanent closure of daylight openings was verified in two cases studies: in the PPMB building, where the north-west saw tooth was totally covered by a black fabric, and CEM EI where the south clerestory was also totally covered, see Figure 4-15.

4.2.4. Indoor surfaces and perception notes

The majority of side walls of case studies have different colours on the upper and lower part. However, in the treatment of the back walls, there is almost the same proportion of variation and uniform colours on the upper and lower part

During daytime, perception notes were taken and summarized in Table 4-3, about the overall space, the level of internal reflections and colours.

The overall space was perceived as neutral to bright in the majority of case studies.

The perception of indoor surfaces, in terms of reflectance values on the ceiling, floor and seating areas are the following:

- High reflection: PMEB and PEG buildings, where there is a combination of white ceilings and light coloured floors, see Figure 4-20
- Moderate reflection: CEM EI, CEM VH, CE CCE, INEFC M, PPMB PMGF and PMVA buildings, see Figure 4-20
- Low reflection: in the CEM LV, CEM VH, CEM RCR buildings, with dark wood on the floor and dark coloured and rough brick walls on side and back walls, see Figure 4-21

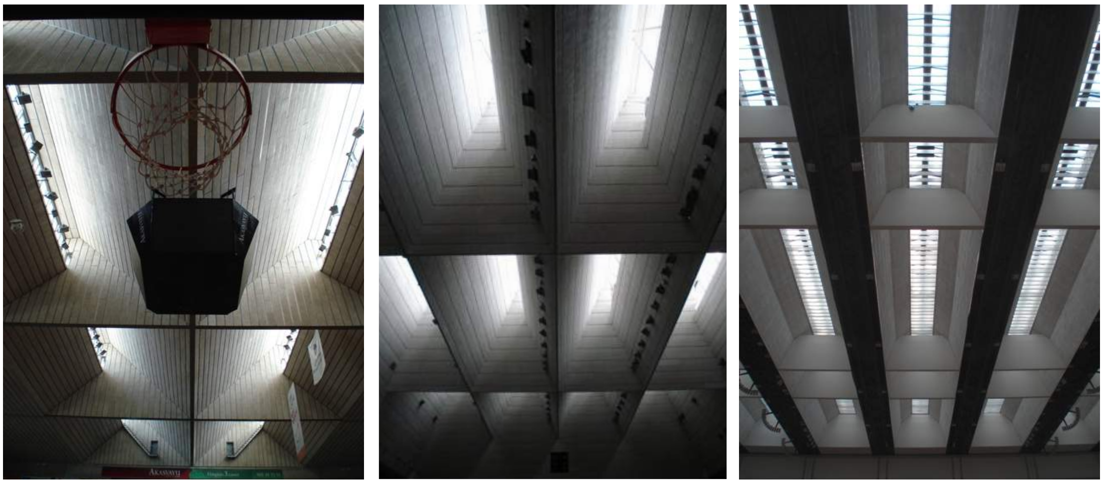


Figure 4-13. Images showing examples of toplighting systems with fixed daylight controls.

PMGF (22/05/2007 1:15 pm, clear sky), left. CEM VH (19/02/2008 1:00 pm, overcast sky), centre.

PEG (23/01/2008 12:50 pm, clear sky), right: integration of splayed surfaces and vertical baffles in the ceiling to diffuse natural light, plus vertical louvres.

Figure 4-14. Images showing examples of sidelighting systems with fixed and movable daylight controls.

CEM VH (19/02/2008 1:00 pm, overcast sky): horizontal louvres, left, and movable blinds in windows, centre. PSJ (17/01/2008 12:20 pm, clear sky): overhang in multilateral windows, right.

Figure 4-15. Images of the CEM EI building, showing the permanent closure of the south clerestory.

CEM EI (05/02/2008 12:10 pm, clear sky) left and right: the light shelve window facing South, was permanent shut-down to avoid sunlight in the court and seating area.

Figure 4-16. Images showing sports halls with predominant warm colours on indoors surfaces.

CEM LV (1st/02/2007 12:30 pm, clear sky), left. CE CCE (13/2/2007, 12:45 pm, clear sky[6]), centre. PPMB (22/05/2007 11:30 am, clear sky), right.

Figure 4-17. Images showing sports halls with a combination of neutral and "warm" colours on indoors surfaces.

PMGF (22/05/2007 1:15 pm, clear sky), left. INEFC M (17/02/2008 12:45 pm, overcast sky[6]), centre. CEM RCR (30/09/2006 10:45 am, intermediate sky), right.

Figure 4-18. Images showing sports halls with predominant "neutral" and "cold" colours on indoor surfaces: floors, ceiling and side and back walls.

CEM EI (05/02/2008 12:10 pm, clear sky), left. INEFC M during fencing competitions (17/02/2008 12:45 pm, overcast sky[6]) centre. PSJ (17/01/2008 12:20 pm, clear sky), right.

[6] Artificial light on.

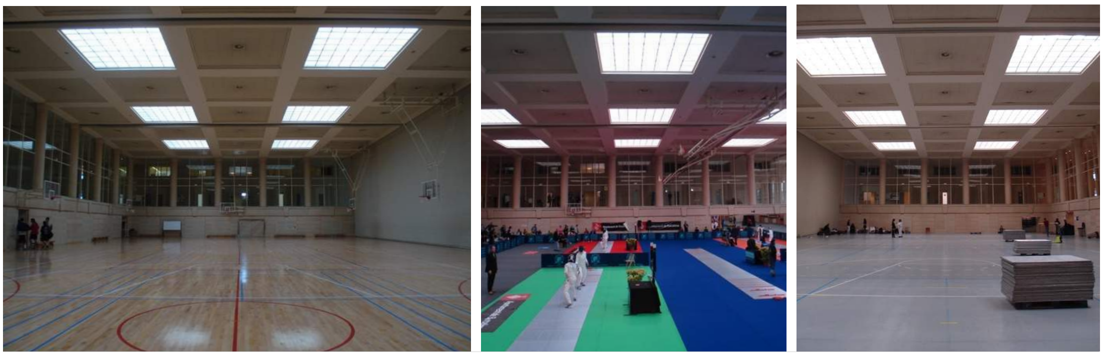


Figure 4-19. Images of the INEFC *building showing training and competition conditions.*

INEFC M: A court during training (6/02/2008 1:05 pm, clear sky), A court during fencing competition (17/02/2008 12:45 pm, overcast sky[6]) centre, and B court during training (17/02/2008 12:45 pm, overcast sky, with artificial lights on), right.

Figure 4-20. Case studies with neutral-bright overall perception of the court.

PMGF (22/05/2007 1:15 pm, clear sky), left. CE CCE (13/2/2007, 12:45 pm, clear sky[7]), centre. PEG (23/01/2008 12:50 pm, clear sky), right.

Figure 4-21. Case studies with neutral-dark overall perception of the court.

CEM LV (1st/02/2007 12:30 pm, clear sky) left. PPMB (22/05/2007 11:30 am, clear sky), centre. CEM VH (19/02/2008 1:00 pm, overcast sky) right.

[7] Artificial light on.

Case studies: reference sample buildings *Main features of the court*	CEM EI	CEM LV	CEM VH	CEM RCR	CE CCE	INEFC	PBFCB	PMEB	PSJ	PEG	PPMB	PMGF	PMVA
Daylighting systems													
Toplighting													
Barrel skylight/ rooflight (lineal)	●	●											●
Piramid skylight/ rooflight (vertical wells)						●							
Flat skylight/ roof window									●				
Pitched skylight/ rooflight (lineal)										●			
Dome skylight/ rooflight									●				
North, North-West facing saw tooth roof (vertical)					●			●			●		
North, North-East monitor			●	●									
East-West monitor roof												●	
Sidelighting													
Windows covering all side wall (unilateral)			●	●									
Lower and middle windows (unilateral)				●	●						●		
Upper and middle windows		●	●	●	●	●					●		●
Upper windows (unilateral)		●							●	●	●		
Upper windows (bilateral)												●	●
Clerestory (bilateral and multilateral)	●						●						
Daylight control and shading devices													
Toplighting													
Translucent glazing	●	●	●		●	●			●	●	●		●
Splayed ceiling	●		●							●	●	●	
Louvres, blades, baffles	●		●	●	●	●				●		●	●
Black-out for top-lighting													
Permanent closure of saw tooth roof								●					
Sidelighting													
Translucent galzing				●									
Louvres and blades			●		●								
Overghang (bilateral/ multilateral)	●								●				
Gallery						●					●		
Light shelves (bilateral)	●												
Black-out for side-lighting			●	●									
Permanent closure of windows	●												
Indoors colour surfaces													
Floor surface													
Side walls (lower part)													
Side walls (upper part)													
Back walls (lower part)													
Back walls (upper part)													
Seats				X	X	X							X
Ceiling													
Perception notes													
Overall perception of the luminous scene (daytime)													
Bright	●				●			●		●		●	
Neutral		●		●		●	●		●		●	●	●
Dark			●	●							●		
Overall internal reflectance													
High internal reflections								●		●			
Moderate internal reflections	●		●		●	●	●		●		●	●	●
Low internal reflections		●		●									
Overall perception in terms of colours													
Cold (blue, light blue, green)			●	●									
Neutral (white, black, grey)	●					●	●	●	●	●		●	
Warm (yellow, orange, red, wood)	●	●		●	●						●		●

Table 4-3. Basic assessment of the reference sample: court features, daylighting systems, control and shading devices, indoor colour surfaces and perception notes.

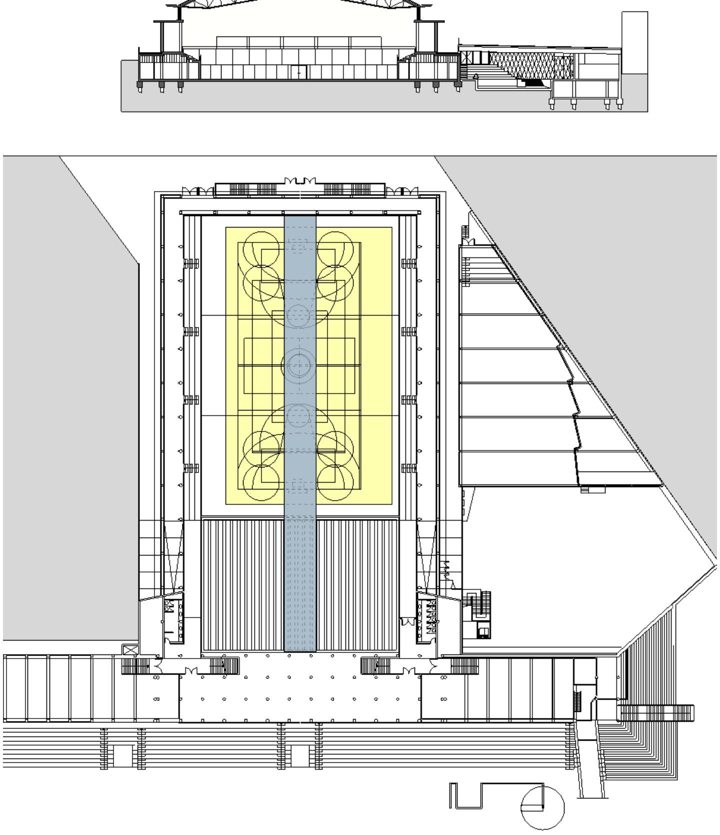


Figure 4-22. Floor plan and cross section (North-South) of the Centre Municipal Esportiu l'Espanya Industrial - CEM EI building.

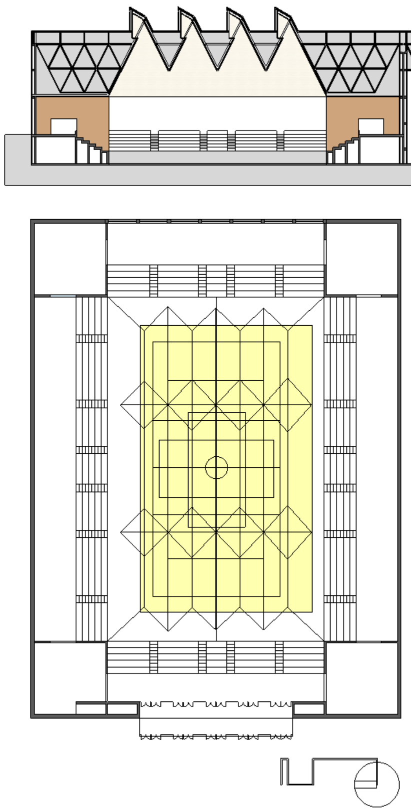


Figure 4-23. Floor plan and cross section (North - South) of the Centre Municipal Esportiu Vall d'Hebron - CEM VH building.

4.3. Final sample

The case studies of the final sample were selected from the reference sample, according to the fulfilment of following requirements:

- If the sports hall was used for Olympic Games in 1992
- If daylighting system provides a minimum of illuminance level to perform the visual task, during daytime and without artificial light
- If toplighting systems are still functioning during this study
- If the building is accessible to perform a comprehensive assessment, including in-situ measurements and detailed objective and subjective visual comfort analysis, as HDRI extended photographic survey and luminance measurements
- If the sports training and competition activities are still held in the building, during this study
- If there are a mixture of different users: as athletes, spectators and eventually, remote spectators and TV broadcasting requirements

Four Olympics sports hall buildings were selected for the final sample, see : CEM L'Espanya Industrial- CEM EI, Figure 4-22, INEFC Montjüic- INEFC M, *Figure 4-24*, CEM Vall d'Hebron-CEM VH, Figure 4-23, and Palau d'Esports de Granollers –PEG, *Figure 4-25*.

Building	**CEM L'Espanya Industrial**	**CEM Vall d'Hebron**	**Institut Nacional d'Educació Física de Catalunya, Montjüic**	**Palau d'Esports de Granollers**
Acronym	**CEM EI**	**CEM VH**	**INEFC**	**PEG**
Sport during Olympics' Games	Weightlifting	Volleyball	Wrestling	Handball
Toplighting system	Lineal half round barrel rooflights + diffusing grey ceiling + gateway	4no. North facing rooflights + diffusing white ceiling	16no. Pyramid rooflights + semi translucent glass + bright ceiling	7no. Pyramid lineal roof-lights + vertical louvers and baffles + diffusing white ceiling
Sidelighting system	North and South clerestories (bilateral) + overhang + light shelf (bilateral)	Est facing window + louvers Glazing West entrance doors + movable blinds (bilateral)	Est facing window + gallery (unilateral)	West- Est facing windows (bilateral)

Table 4-4. Main features and images of the four Olympic buildings selected for the final sample: CEM EI, CEM VH INEFC and PEG.

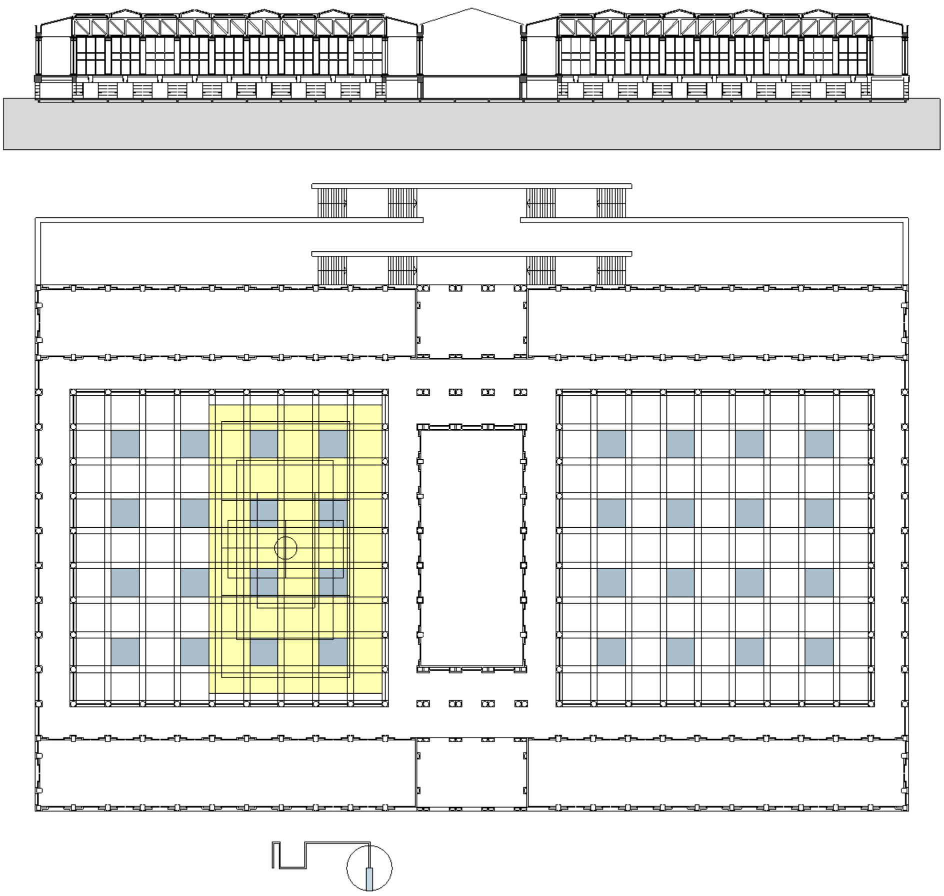


Figure 4-24. Floor plan and cross section (West - Est) of Institut Nacional d'Educació Física de Catalunya Montjuïc-INEFC building.

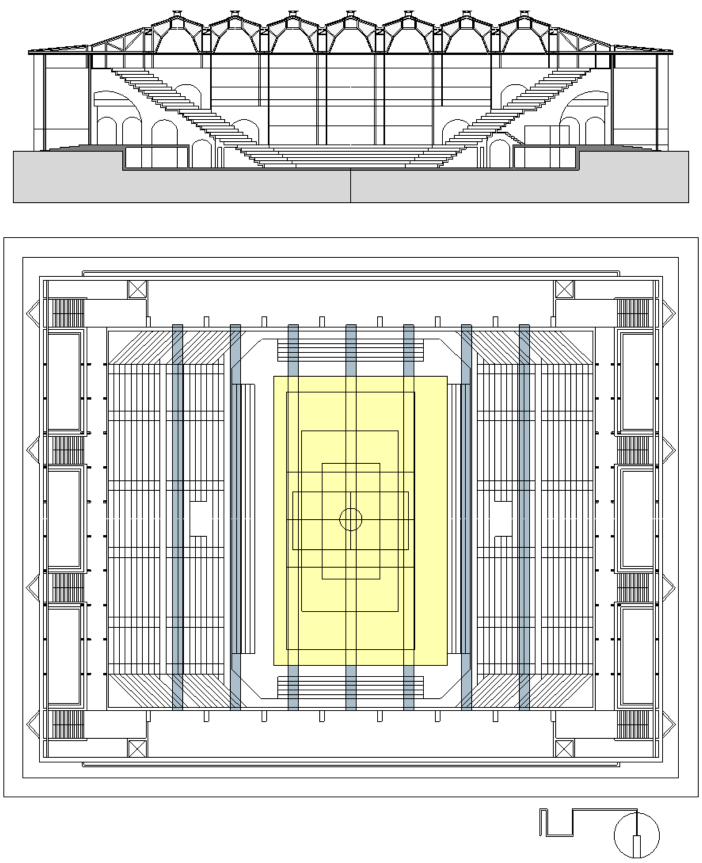


Figure 4-25. Floor plan and cross section (East - West) of the Palau d'Esports de Granollers PEG building.

4.4. Chapter conclusions

Luminous space

Although all the sports halls selected have the same type of sports facility: the triple pavilion PAV-3, the resulting architectonic design is not standard and depends of many factors. All the architectural elements of court are defining and impacting the perception of the luminous environment in terms of: shape and orientation of daylight systems implemented, as well as materials, texture and colours of the indoor surfaces.

The indoors surfaces of the court could vary due to competition requirements. These variations found are: colours, reflectance and finishing material textures. Because of these, the visual perception of the overall space is noticeably modified.

Daylight systems

The majority of the cases studies of the reference sample have a combination of toplighting and sidelighting systems. However, one building the PPMB, has exclusively a sawtooth facing North.

Skylights/rooflights are the main daylighting system in the majority of buildings, followed by the saw tooth. The less represented toplighting systems are the North monitor and the East-West monitor roofs, in the reference sample

Most of the case studies have windows as the main sidelighting system. The majority of them are bilateral or multilateral respect to the court, located in the upper and middle part of the sidewalls.

The use of daylight systems has been verified in the majority of case studies of the reference sample, which are providing natural light for minimum lighting requirements, in specific conditions. However, in two case studies both toplighting and sidelighting systems were totally or partially shuttered-down.

Daylight control and shading devices

The majority of solar protection and daylight controls found in the reference sample are passive.

Considering toplighting systems, the most used controls to diffuse daylight are translucent glazing, splayed ceilings, louvres and baffles. However, there is a lack of movable and black-out devices.

Concerning the sidelighting systems, louvres, blades, overhangs, light shelves and translucent glazing are the most frequent fixed controls found for natural light. Two examples, have movable blinds to black-out windows, covering all side wall or back wall.

In the majority of the case studies, there is a lack of movable devices to regulate and black-out daylighting, most of all, in toplighting.

Subjective perception

The majority of the sports halls selected have neutral or bright perception of the court and surroundings, from subjective assessment of the overall space. This could be correlated with the performance of daylighting systems and internal reflections. High and moderate internal reflectance was also perceived, most of all on the floor, ceiling and side walls.

Finally, site visits and basic and subjective assessments of daylighting systems have contributed to the design of the methodology proposed for this work, including the final sample selection for further comprehensive assessments.

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5

Visual comfort in existing sports halls

This chapter presents the discussion of results from the visual comfort assessment performed in the sports halls. These results are based on the in-situ measurements, objective and subjective assessments. This chapter is divided in two parts. The first part presents the discussion of the results of the reference sample, including quantitative and qualitative parameters evaluated. The second part shows the detailed assessment results obtained from the final sample by HDR images and luminance analysis. Examples of the most frequent situations of potential visual discomfort are also illustrated with case studies.

As a result of the visual comfort assessment developed during this thesis, design guidelines for the optimization of daylight in sports halls in Catalunya were compiled with the support of Generalitat de Catalunya, Secretaria General de l'Esport CCE, Consell Català de l'Esport, see Appendix I.

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5.1 Visual comfort assessment: reference sample results

The assessment of the visual comfort in the reference sample is presented in the first part of this Chapter. Based on the 1st stage of in-situ measurements, results of the quantitative and qualitative parameters include: horizontal illuminance levels - E_h (lx), Daylight Factor - DF (%), uniformity - U on the court, glare sources – G_s in the field of view - FOV. Sunlight penetration in the court and seating areas, potential glare sources and excessive contrast identified in the users' field of view - FOV are also presented, based in the subjective assessment and photographic surveys, see Appendix III for the complete results.

The in-situ measurements were taken in specific conditions, according to the methodology proposed in Chapter 3: Date (Day/Month/Year), Time (expressed in Central European Time - CET or UTC/GMT +1h in winter, Central European Summer Time - CEST or UTC/GMT +2h in summer, according with the Daylight-Saving Time) and sky conditions (clear, overcast, intermediate with clouds). Accordingly, these results are given as reference values and they cannot be extrapolated.

5.1.1 Natural lighting levels on the court

The minimum level required to carry out the visual task in sports halls for training is 200-300lx. For regional, national and international competition the levels are raised up from 500lx to 1000 lx depending on the kind of sport and if TV broadcasting is required.

The results of measurements in the case studies are described according to the different results of average of horizontal illuminance E_h level and daylight factor DF, carried out during daytime and with or without the contribution of artificial light:

Horizontal illuminance -E_h: clear sky

Results of the average horizontal illuminance E_h level, under clear sky conditions and without artificial light are the following:

- E_h average < 150 lx: PBFC, CEM VH and PMGF, see Figure 5-1
- E_h average ≅ 200 – 300 lx, training activities: PSJ- $E_{h\ ave}$=239 lx, CECCE- $E_{h\ ave}$=242 lx, PPMB- $E_{h\ ave}$=254 lx, INEFC- $E_{h\ ave}$=282 lx, see Figure 5-2
- E_h average ≅ 300 – 500 lx, regional competitions: LV (432 lx) and INEFC, see Figure 5-3
- E_h average > 500 lx, national and international competitions: CEM EI (550 lx, 655 lx) and PEG (540 lx, 729 lx), see Figure 5-4

Artificial lighting could be required in specific situations, depending on the level of competition, as national, international and TV broadcasting requirements, e.g.: the INEFC building, see Figure 5-6.

Daylight factor - DF%: overcast sky conditions

Although a minimum DF% isn't established yet for sports halls, a value of DF% 2,0 is considered generally as a good level of daylight.

Figure 5-1. Case studies where the average horizontal illuminance level in the court is: $E_{h\ ave} < 150$ lx.

PBFCB (20/02/2008 11:00 am, overcast sky) left. CEM VH (19/02/2008 1:00 pm, overcast sky) centre.

PMGF (22/05/2007 1:15 pm, clear sky) right.

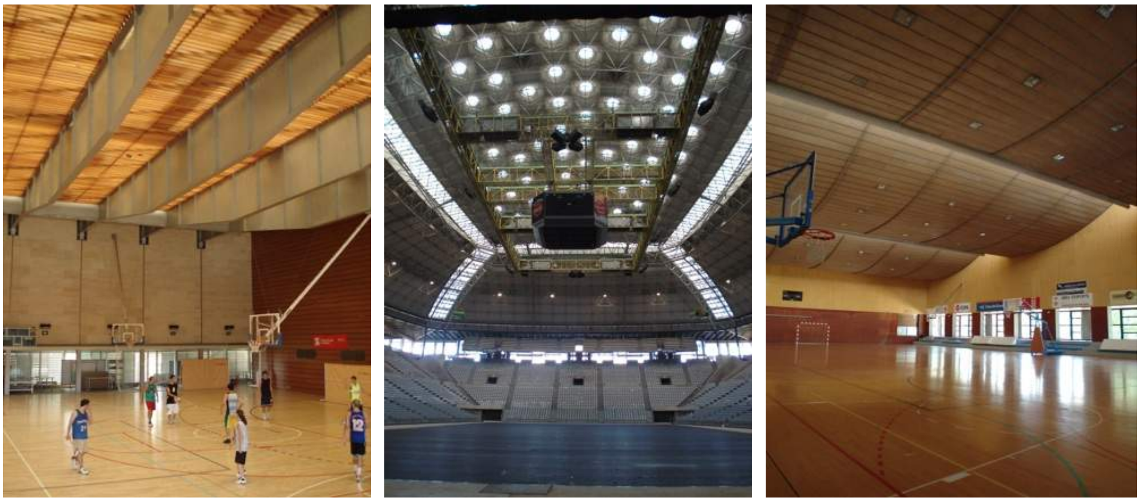

Figure 5-2. Sports halls case studies where the average horizontal illuminance level in the court is: $E_{h\ ave} \cong 200 - 300$ lx.

CECCE (13/02/2007 12:45 pm clear sky) left. PSJ (17/01/2008 12:20 pm, clear sky) centre.

PPMB (22/05/2007 11:30 am, clear sky) right.

Figure 5-3. Sports halls case studies where the average horizontal illuminance level in the court is: $E_{h\ ave} \cong 400 - 500$ lx.

CEM LV (1st/02/2007 12:30 pm, clear sky) left. INEFC (6/02/2008 1:05 pm, clear sky) right.

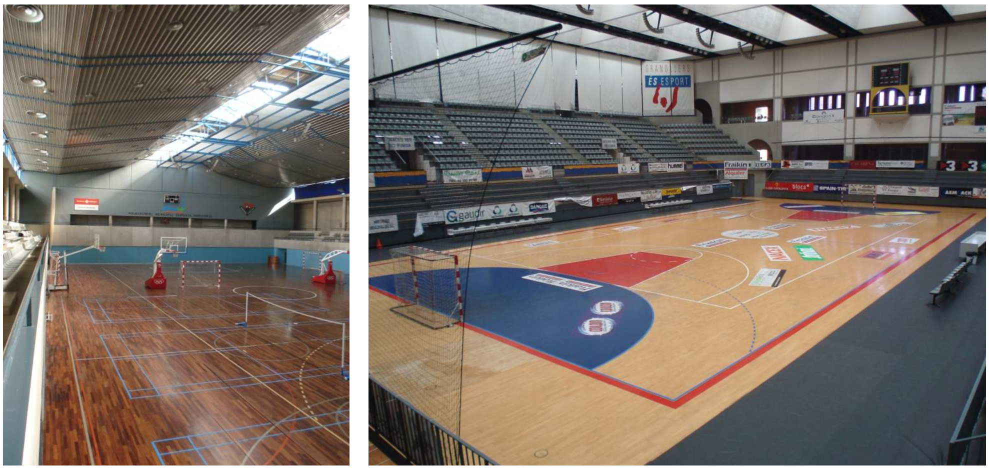

Figure 5-4. Sports halls case studies where the average horizontal illuminance level in the court is: $E_{h\ ave} > 500$ lx.

CEM EI (05/02/2008 12:10 pm, clear sky) $E_{h\ ave}$= 550 lx, left. PEG (23/01/2008 12:50 pm, clear sky) $E_{h\ ave}$=729 lx, right.

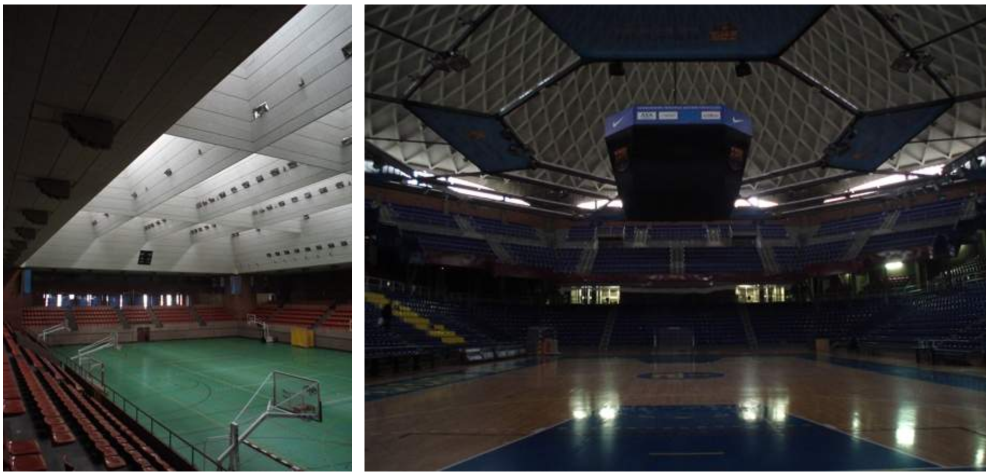

Figure 5-5. Case studies where the average daylight factor in the court is: $DF\%_{ave} < 1,0\%$.

CEM VH (19/02/2008 1:00 pm, overcast sky) DF% ave ≅ 0,5%, left.

PBFCB (20/02/2008 11:00 am, overcast sky) DF% ave ≅ 0,2%, right.

Figure 5-6. Case studies where the average daylight factor in the court is: $DF\%_{ave} > 1,5 < 2\%$ in the court.

PEG (20/02/2008 12:50 pm, overcast sky) $DF\%_{ave}$ ≅ 1,80%, left.

CEM EI (19/02/2008 10:45 am, overcast sky) $DF\%_{ave}$ ≅1,75%, centre.

INEFC (17/02/2008 1:05 pm, overcast sky) $DF\%_{ave}$ ≅1,65%[1], right.

[1] artificial light on during measurements and survey.

Figure 5-7. Sports halls buildings where the horizontal illuminance uniformity on the court is: U < 0,4.

CECCE (13/2/2007 12:45 pm, clear sky) U ≅ 0,32, left. CEM LV (1st/02/2007 12:30 pm, clear sky) U ≅ 0,24, centre. CEM EI (05/02/2008 12:10 pm, clear sky) U ≅ 0,37, right.

Figure 5-8. Sports halls buildings where the horizontal illuminance uniformity on the court is: 0,4 >U ≅ 0,5.

CEM VH (8/11/2006 1:30 pm, clear sky) U ≅ 0,42, left. Half court of INEFC (6/02/2008 1:05 pm, clear sky) U ≅ 0,41, centre. PPMB (22/05/2007 11:30 am, clear sky) U ≅ 0,52, right.

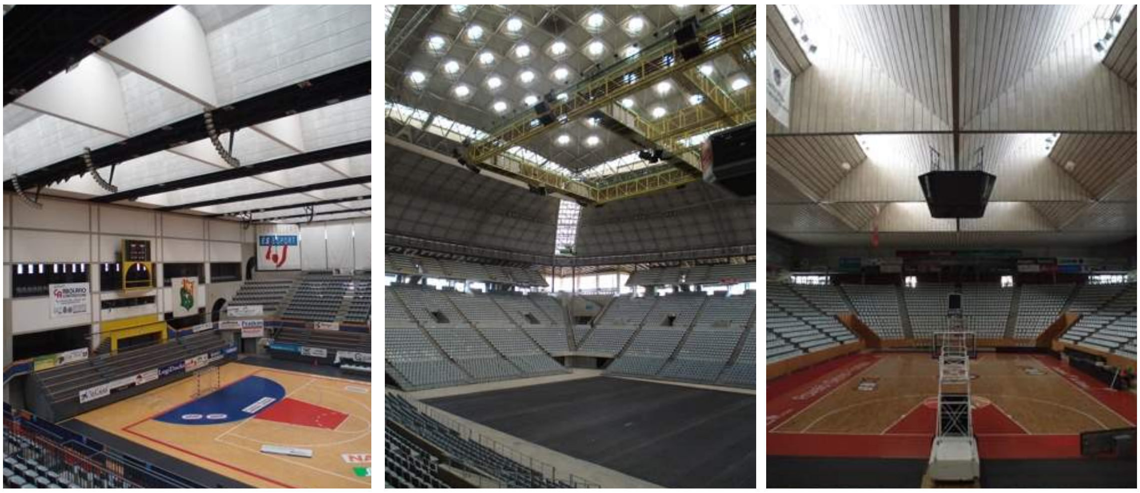

Figure 5-9. Sports halls buildings the horizontal illuminance uniformity on the court is: U > 0,5.

PEG (23/01/2008 12:50 pm, clear sky) U ≅ 0,75, left. PSJ (17/01/2007 2:00 pm, clear sky) U ≅ 0,62, centre.

PMGF (22/05/2007 1:15 pm, clear sky) U ≅ 0,76, right.

The DF % values have been verified for five case studies, when measurements were carried out under overcast sky conditions.

- DF < 1,0%: CEM VH and PBFCB buildings, see Figure 5-5
- DF >1,5% < 2%: PEG, CEM EI and INEFC buildings, the mean DF% values are below 2%, but with a minim of 1,5%, see Figure 5-6

Minimum levels for training and competition could be achieved with the addition of artificial light in specific situations, e.g.: the INEFC building in the case of the International Fencing Competition, see Figure 5-6.

5.1.2 Illuminance uniformity - U

The recommended uniformity value for the playing area in sports halls is U ≅ 0,5 or above (EN 1293:199). The uniformity results in the reference sample are the following:

- U < 0,4: in the CEM EI, CE CCE and PBFCB buildings, the uniformity is below 0,4, see Figure 5-7
- U > 0,4 ≅ 0,5: in some case studies, as the CEM LV, CEM VH and INEFC buildings, a minimum of uniformity level is achieved in the court, with values between 0,4 and 0,5, see Figure 5-8
- U > 0,5: in three case studies PSJ, PEG, PPMB and PMGF buildings, a good uniformity level could be achieved, with values higher than 0,5, see Figure 5-9

5.1.3 Glare sources - G_s

The discomfort and disability glare could be critical issues for the sports activities, affecting athletes, spectators and TV- television broadcasting. Veiling reflections and the vision of external elements through the openings could generate discomfort and absolute glare due to the high values of luminance.

The case studies are classified according to the type of glare sources identified in the users' FOV by daylighting systems as follows:

- Direct light or sunlight in the court: sunlight penetration and sun-patches on the floor
- Reflections of direct and diffuse light on reflective surfaces, particularly on the floor
- Direct view of glazing areas or openings without diffusion or control, including external reflections and the nearby sun lighted façades (through the windows)

Direct light- sunlight

The direct light or sunlight in the court or playing area and seating area by sidelighting and toplighting openings could be the cause of discomfort glare and disability glare. This could affect mostly athletes, in the first place, and spectators and TV broadcasting conditions, in second place.

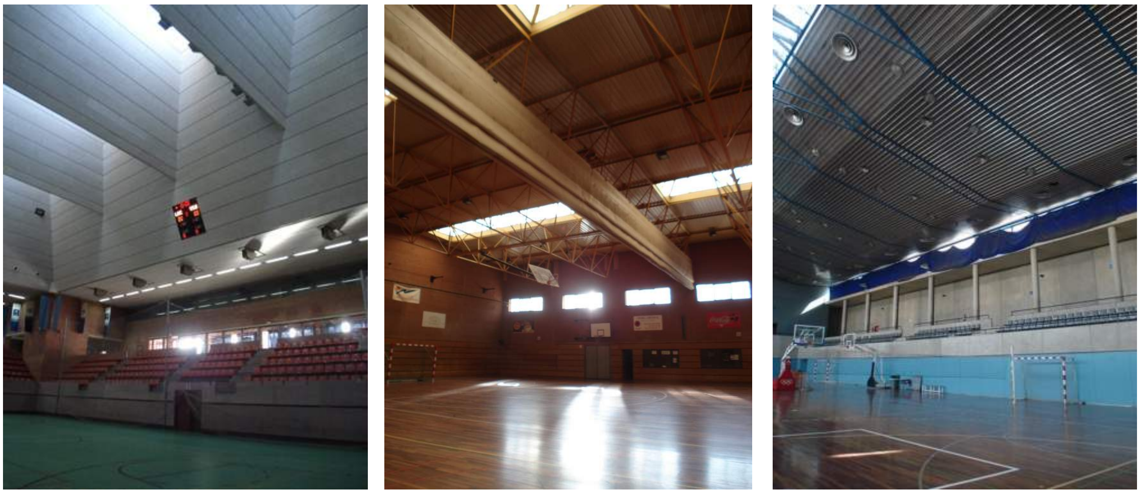

Figure 5-10. Case studies showing sunlight penetration on the court by sidelighting openings.

CEM VH (12/01/2008 1:30 pm, clear sky) left. CEM LV (1st/02/2007 12:30 pm, clear sky) centre.

CEM EI (05/02/2008 12:10 pm, clear sky) left.

Figure 5-11. Case studies showing sunlight penetration on the court and seating areas by toplighting openings.

CEM CR (30/09/2006 10:45 am intermediate sky) left. CEM EI (5/02/2008 12:10 pm, clear sky) centre and right.

Figure 5-12. Case studies showing reflections on the court surface, mostly by sidelighting openings.

INEFC (6/02/2008 1:05 pm, clear sky) left. PPMB (22/05/2007 11:30 am, clear sky) centre.

CEM CR (30/09/2006 10:45 am, intermediate sky) right.

In the CEM EI, CEM LV and CEM VH buildings there are potential glare sources due to sunlight in the court by sidelighting systems. For example, in the case of CEM EI, the window facing south has been permanently closed with a curtain to avoid the sunlight penetration on the court, see Figure 5-10. In the CEM EI and CEM RCR buildings there are potential glare sources of sunlight due to the toplighting systems, see Figure 5-11.

Reflections on interior surfaces

Results of situations with direct or indirect light that could cause glare discomfort and disability glare due to veiling or specular reflections on glossy and/or bright surfaces are presented. In particular, the reflections generated from windows on polished floors are frequent sources of glare for all the users.

In the majority of the case studies, examples of that were frequent in the following buildings: CEM EI, CEM LV, CEM CR, CE CCE, INEFC, CCE, PEG, PPMB, PMGF and PMVA buildings, see Figure 5-13 and Figure 5-14.

External reflections and view of the sky

The direct light or sunlight reflected in nearby façades or outdoor elements is the most common situation found in case studies, including specular reflexions from near surfaces as glass or bright façades. Likewise, it is the vision of the sky (luminance of the clear sky for example: > 2.000 - 8.000 cd/m^2).

The most critical situations were found in the CEM CR, CE CCE, INEFC and PPMB, see Figure 5-14, Figure 5-20 and Figure 5-22.

View of daylight openings

The vision of glazing surfaces from daylight systems are potential glare sources to users, see Figure 5-13, Figure 5-14, Figure 5-15, and classified as follows:

- Windows
- Clerestories, roof lights and roof monitors

The vision of glazing areas of sidelighting systems, such as windows, are very likely potential glare sources to all users, especially when covering different portions of side walls. Moreover, they could generate excessive contrast and specular and veiling reflections on the court surface.

Situations of risk of glare by the view of clerestories and toplighting openings have been found in the case studies of CEM EI, CEM CR, PPMB, and PMGF buildings, but in specific users' view directions and less frequency due to the relative position in the users' FOV, see Figure 5-11. This could be critical in sports where athletes spend most of their time looking towards the ceiling, following high level shots of a small and fast moving ball, e.g.: badminton (Sport Scotland 2002; 2012).

5.1.4 Shading and daylight control devices

The shading devices and daylight controls could be needed to avoid discomfort or disability glare, when direct light is hitting the court, seating area and/or when there are very bright surfaces in the users' FOV.

Shading devices, dimming controls and the total black-out of daylighting systems could be essential for TV broadcasting of sports competitions and for the realization of non-sporting events.

Figure 5-13. Case studies with direct view of sidelighting openings, placed in the lower and middle parts of side walls.

CE CCE (13/02/2007 12:45 pm, clear sky1) left. PPMB (22/05/2007 11:30 am, clear sky) centre.

CEM RCR (30/09/2006 10:45 am, intermediate sky) right.

Figure 5-14 Case studies with direct view of sidelighting openings, placed in the middle and upper parts of side walls.

PPMB (22/05/2007 11:30 am, clear sky) left. INEFC (17/02/2008 12:45 pm, overcast sky1) centre.

CECCE (13/2/200712:45 pm, clear sky1) right.

Figure 5-15 Case studies with direct view of sidelighting openings, placed in the upper part of side walls.

PMVA (20/09/2006 1:30 pm, clear sky) left. CEM LV (1st/02/2007 12:30 pm, clear sky) centre.

CEM EI (05/02/2008 12:10 pm, clear sky) right.

Apart from the direct view of sidelighting openings, it could be absolute glare situations caused by veiling reflections on the court surface due to windows and shiny floor finishing.

The results are classified according to the type of daylight system as follows:

- Sidelighting: there is a lack of movable shading devices in the majority of case studies, with the exception of black out in windows found in CEM VH, CEM CR. Other devices have shown a low performance or were out of service, e.g.: in the CEM VH building with louvers on the side windows, see Figure 5-19 and Figure 5-24
- Toplighting: there is a lack of mobile shading devices and black out in the majority of case studies, with the exception of passive devices such as screens, louvers and baffles found in CE CCE, CEM CR, CEM EI, CEM VA, CEM VH, PEG, PMGF buildings, see Figure 5-16

Other devices have been verified to be used as blackout for windows, such as the internal roller blinds installed for internal division of the court.

Examples of this have been found in the INEFC building, in relation to the TV broadcasting requirements for the International Fencing Competition, see Figure 5-18. The TV camera was positioned facing the opposite window, so the side window had been blocked to avoid glare and the backlight effect. The interior fabric division was operating as a shading device in two modes: partially drawn to cover the middle part of the side window for the semi-final competitions, and fully drawn for the final competition. Another example is the PMEB building, see Figure 5-17. The North sawtooth roof has been totally shutdown due to the infeasibility to control daylight levels of the court, for basketball televised competitions. In these situations, the use of the artificial light is required, with artistically and scenography purposes.

5.1.5 Contrast and adaptation level

The observer's eye adapts to the average luminance of the object and its immediate surroundings in the FOV. High variations of luminances respect to this average value are potential risk of discomfort glare by adaptation, when the eye is not able to adapt in a short time, taking into account the minimum accommodation time and the direction of adaptation (from low to high, and from high to low).

Excessive contrast on adjacent surfaces

Surrounding architectural elements with different brightness or luminances could cause contrast glare when there are adjacent or closely placed surfaces. This could produce visual discomfort and also increase the difficulty of the dynamic visual task when users are tracking objects in the space. It is because a non-uniform background is perceived by users and also it is fluctuating in terms of brightness during the visual task. Different quantities of light hitting the surrounding horizontal and vertical surfaces also could cause excessive contrast.

The most common examples found in the reference sample are the following:

- Hard frames
- Backlight effect
- Luminous patterns

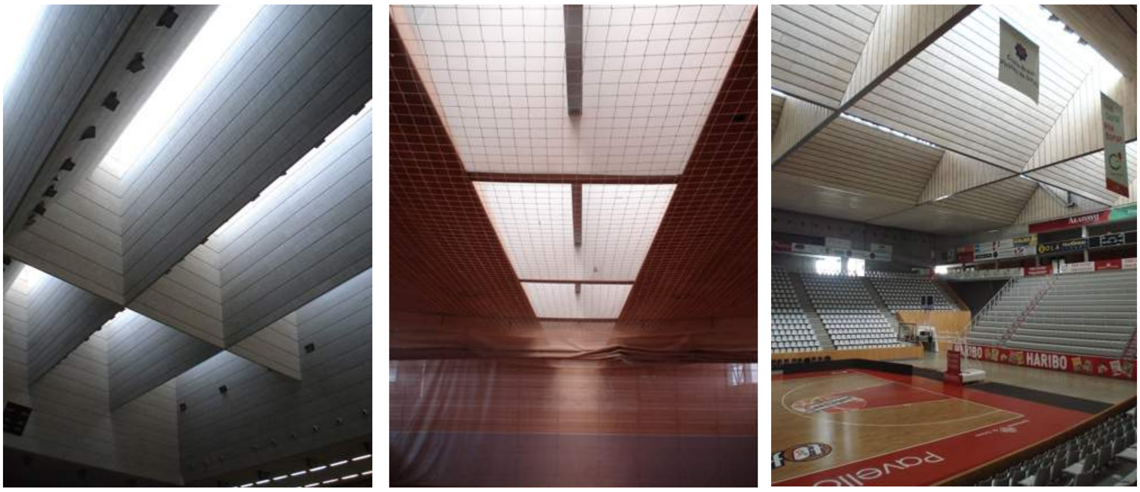

Figure 5-16. Case studies with passive daylight controls in toplighting: vertical baffles and splayed frames.

CEM VH (12/01/2008 1:30 pm, clear sky) left. PMVA (20/09/2006 1:30 pm, clear sky) centre.
PMGF (22/05/2007 1:15 pm, clear sky) right.

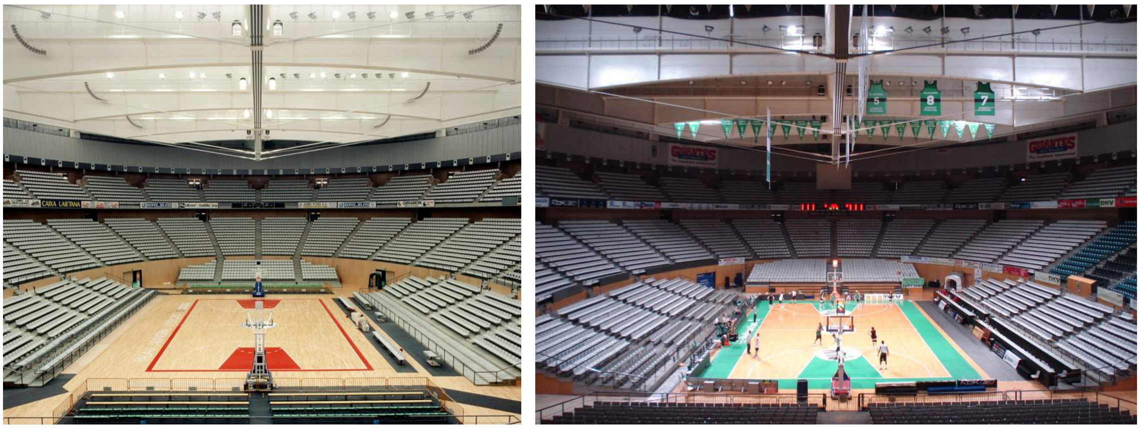

Figure 5-17. Images of Palau Municipal d'Esports de Badalona –PMEB.

The court with daylight by the saw tooth roof, when the building was inaugurated for the 1992 Barcelona Olympic Games, left (Source: ©Gina Barcelona Arquitectes: http://ginabarcelona.com). The court with only artificial light, during daytime, due to the saw tooth roof has been permanently shut-down, right.

Figure 5-18. Images of the INEFC sport hall building during an International Fencing Competition.

INEFC (17/02/2008 12:45 pm, overcast sky1): competitions during the day, left. Semi-final competitions, centre. Final competition and TV broadcasting conditions, right.

The internal division has been operating as a black-out, in part and fully drawn mode to cover the side windows for the TV broadcasting requirements. The resulting effect, illustrated by images, is the re-distribution of luminances in the FOV: improving the luminance' uniformity, reducing the excessive contrast or difference between minimum and maximum luminances. Finally, the space could be perceived as brighter, without the contribution of the side windows.

Hard frames

The contrast between bright openings and opaque surrounding surfaces not properly lit could be excessive if there is no transition between them. Moreover, if those adjacent surfaces are dark and also not sufficiently day-lit the contrast could be extreme (Moore 1985). The most common examples of hard frames are the following:

- Sidelighting: CEM EI, CEM LV, CEM VH, CE CCE, PBFCB, PSJ, PEG and PMVA buildings
- Toplighting: CEM LV, CEM RCR, INEFC, PEG and PMVA buildings

High contrast between windows and side walls have been found in the majority of case studies. The bright small and medium size glazing areas with not enough daylight hitting the side opaque surfaces might increase the perception of excessive contrast and the backlight effect. For example, in the CEM VH building the contrast between the ceiling and surrounding side walls is high, see Figure 5-19, because the side walls are not day-lit. Additionally, these walls have a low reflectance factor due to their texture and colour. Other examples of this are also large windows with contrasting surroundings, e.g.: CEM RCR, INEFC and PPMB buildings.

High contrast between toplighting openings and ceiling have been found in five case studies, see Figure 5-19 and Figure 5-23.

Backlight effect

Backlight occurs when the background area of the visual field - FOV is brighter (brilliance) than the target or the object that is wanted to see. The light direction also is opposite to the sense of the sight or view direction, so the object is illuminated from the back. The visual task becomes difficult while the target object cannot be accurately perceived, in terms of colours and details.

The majority of examples found the backlight effect is caused from windows, in frequent user's view–directions: CEM LV, CEM VH, CEM RCR, CE CCE, INEFC and PPMB buildings.

Additionally, the directional light from windows might be contrary to the users' views, see Figure 5-20 and also, it could cause shadows in the court, as athletes or objects.

Luminous patterns

Two case studies have been found in the PMEB and PEG buildings, where the adjacent surfaces have very dissimilar brightness, in terms of reflectance values and colours.

In the PEG building, the use of black with 0,10 of reflectance and white, with 0,90 in the ceiling generates a striped black and white pattern, see Figure 5-19. In the PMEB, the surrounding surfaces of windows can generate a striped vertical pattern, with a dark and dissimilar colour that the rest of side walls, see Figure 5-22.

5.1.6 User interaction with the luminous environment

The interaction of dynamic users in movement into the space with the physical environment, changes the perception of the size and the position of architectonic elements in the user's visual field. This could potentially affect their visual task in different levels, related to the relative size and position of the glare sources, as the proximity, view direction, angle of sight, central or peripheral situation of the glare source in the FOV.

View direction and position of the user

Figure 5-19. Case studies with excessive contrast: hard frames and different reflectance on adjacent surfaces.

CEM VH CEM VH (8/11/2006 1:30 pm, overcast sky): hard frames on side walls, left.

CEM CR (30/09/2006 10:45 am, intermediate sky): hard frames on side walls, centre.

PEG (20/02/08 1:20 pm, overcast sky): hard frames in side walls and luminous pattern on the ceiling, right.

Figure 5-20.Case studies with backlit effect in specific view directions due the sidelighting openings.

INEFC (17/02/2008 12:45 pm, overcast sky[1]) hard frames on side walls and ceiling and backlit effect in the main view direction of spectators and TV, left.

CE CCE (13/2/2007 12:45 pm, clear sky[1]) hard frame and backlit effect from window, right.

Figure 5-21. Case studies showing situations of excessive contrast between windows, ceiling and side walls.

CEM EI (05/02/2008 12:10 pm, clear sky) left. CEM VH (02/12/2006 2:00 pm, overcast sky), centre and right.

View direction and position of the user

The relative position of the glare sources could change when athletes are in movement in the space. Moreover, it is common that all users adjust and change view directions while they are tracking visual targets.

Situations of discomfort or disability glare can be critical when the users are facing potential glare sources or the gaze is meeting glare sources (closeness to the target area), according to the following:

- Athletes facing sidelighting openings: CEM CR, CE CCE, PPMB, INEFC buildings, see Figure 5-22 Figure 5-23
- Athletes facing toplighting openings: CEM EI, CEM RCR, PMEB and PMFG buildings, see Figure 5-23
- Spectators and TV cameras facing sidelighting openings: PMGF, CEM VH, PSJ, INEFC buildings, see Figure 5-24

In the majority of case studies common athlete's view directions have been found towards side openings or facing windows.

The view towards the ceiling is a less frequent view direction, but highly likely in specific sports. Frequently, it could occur when the athletes are tracking a ball and this can be contrasted over toplighting openings and the ceiling. For example, in the PMEB, the critical situations could be when athletes could face direct light or the view of the sky trough the saw tooth openings, see Figure 5-23.

Situations have been found when spectators and TV cameras views face sidelighting openings. These situations could cause visual discomfort, absolute or contrast glare for spectators. It could be also an issue for TV broadcasting conditions, see Figure 5-24.

5.1.7 Luminous environment: overall perception

The perception of the overall scene depends on many factors as described previously, see section 4.2.4 in Chapter 4. The court and surrounding areas are affected by indoor reflections from architectonic surfaces, lighting levels and contrast between bright and dark elements. Examples of the INEFC building have shown that the addition of light and vibrant coloured surfaces on the floor and interior surfaces could transform the indoor light reflections. As a consequence of that, the overall perception could be changed in terms of contrast and brightness. The luminous scene could appear less or more bright as well despite the fact that daylight and artificial lighting levels have been unaltered, see Figure 5-25 and Figure 5-26.

Dark scene

The combination of different factors could be perceived by users as a dark or gloomy scene despite the quantity of light in the court. Low daylight levels E_h, the colour temperature resulting from diffuse daylight, low reflections due to dark surfaces and cold colours are the main factors found in the examples. The textured/rough and dark coloured side walls could increase the perception of the dark environment in the CEM VH building, as explained in 5.1.5, see Figure 5-19.

Figure 5-22. Case studies showing situations where athletes, spectators and TV broadcasting cameras could face windows.

CEM CR (30/09/2006 10:45 am, intermediate sky) left. PPMB (22/05/2007 11:30 am, clear sky) hard frames and luminous patterns on side walls, centre. CE CCE (13/2/2007 12:45 pm, clear sky1), right.

Figure 5-23. Cases studies showing view directions and users positions into the court, where athletes could face toplighting and sidelighting openings.

PPMB (22/05/2007 11:30 am, clear sky) left. PMGF (22/05/2007 1:15 pm, clear sky) centre.

CEM RCR (30/09/2006 10:45 am, intermediate sky), right.

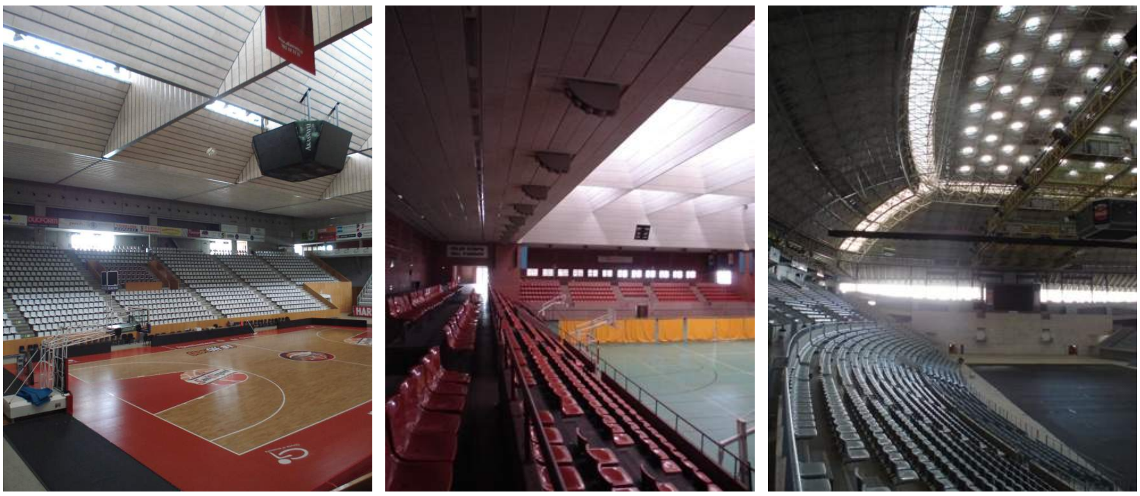

Figure 5-24. Images showing situations of spectators and TV broadcasting conditions facing windows.

PMGF (22/05/2007 1:15 pm, clear sky) left. CEM VH (8/11/2006 1:30 pm, overcast sky) centre.

PSJ (17/01/2007 2:00 pm, clear sky), right.

Figure 5-25. Images of the INEFC with different court configurations but similar natural and artificial lighting levels

INEFC (17/02/2008 12:45 pm, overcast sky1 with artificial lights on) during International Fencing Competition, left.
INEFC (6/02/2008 1:05 pm, clear sky) during training conditions or original features of the court, right.

Figure 5-26. Images of the PSJ with different court configurations but similar natural and artificial lighting levels.

PSJ (04/01/2007 1:20 pm, cloudy /clear sky[1]) with original features of the court, left.

PSJ (02/12/2009 10:20 am, clear sky[1]) configuration for the Tennis Davis Cup International Competition, right.

5.2 Visual comfort assessment: final sample

The second part of the visual comfort assessment is the detailed analysis of qualitative parameters based on the HDR calibrated images obtained for the final sample, resulting in 4 case studies: CEM EI, CEM VH, INEFC and PEG buildings.

Glare sources- G_{source} and luminance L analysis

The analysis of HDR images is carried out by PHOTOSPHERE software (Ward 2014, Version 1.8.16U) with the aim to identify potential or existing disability glare and discomfort glare situations.

The luminance values obtained in-situ and the resulting values after post-calibration process of HDR images are also shown in False Colour Visualization: red dots for in-situ measurements and black dots for post-calibrated values by PHOTOSPHERE software (Ward 2014, Version 1.8.16U).

5.2.1 Centre Esportiu Municipal de l'Espanya Industrial - CEM EI building

Athlete user

The glare sources G_{source} with maximum values identified in the final sample are from clerestories, as shown in C1 and C4. It can be in the foveal region, depending on the view direction and the position of the target and especially from external reflections, as shown in C2, C4 view directions and Table 5-1. There are potential glare sources of direct light from the clerestory oriented to the South especially where there are no blinds, see C2 in

Figure 5-27 and Figure 5-29. In the second place, the potential glare source is the central skylight, especially when the translucent surface allows the vision of the sky. However, skylights are generally in the far surrounding and peripheral or background area of the FOV.

Adaptation glare could be more frequent due to excessive contrast between clerestories and adjacent walls, see Table 5-1.

Spectator / remote spectator and television broadcasting - TV user

For spectator user, there is a high risk of glare in the foveal and near surrounding areas from clerestories. In particular, when users are facing them, as shown in B1. There are potential glare sources of direct light from the clerestory oriented to the south and central skylight. In the second place, the central skylight is a potential glare source, but usually in the far and peripheral area, see B1 and B4, see Figure 5-28 and Figure 5-30.

Adaptation glare by hard frames between windows and ceiling could be frequent due to excessive contrast see Table 5-2 and Figure 5-29. As well, it could be due to skylights, but commonly placed out of the main areas 1 and 2 or in the peripheral area.

CEM EI (19/10/2009, cloudy sky):

Court C4: 12:13 pm		Potential Glare Sourcess >(7x)			**168**
Region		L In situ (1)	L HDRI (2)	Contrast ratio: target(1)	Contrast ratio: target(2)
1	Target (2º)	17	24	-	-
2	Ceiling		246	-	0,1
2	Glazing area window (near area)	1.478	2.170	61,6	90,4
2	Side Wall- concrete	54	111	2,3	4,6
3	Side Wall- orange	34	60	1,4	2,5
3	**Glazing area window***	**3.336**	3.330	139,0	138,8
3	Floor		129	-	5,4

* Calibration value

Frames	L max	L min	Contrast ratio:
Skylight opening/ adjacent ceiling	-	-	-
Windows opening/ adjacent wall	1.478	17	86,9

Table 5-1. Luminance contrast for athlete user in CEM EI building: C4 view direction.

Luminance values >168,0 cd/m² could be potential G_{source}, maximum contrast found by windows in regions 2, 3.

Where:

$Potential\ Glare\ Sources > (7x)$: threshold obtained multiplying the luminance average value of the task L_{task} or target by 7 times

L_{task}: luminance of the target (2º) or task (cd/m²)

$L\ in\ situ$ (1): luminance value obtained from in situ spot measurements (cd/m²)

$L\ HDRI$ (2): luminance value of interior surfaces obtained from HDR images, after calibration process by PHOTOSPHERE software (Ward 2014, Version 1.8.16U) (cd/m²)

$Contrast\ ratio$: $(target\ 1)$: ratio between the target against L in situ (1) values, from architectonic elements located in regions 2 or 3

$Contrast\ ratio\ (target\ 2)$: ratio between the target against L HDRI (2) values, from architectonic elements, located in regions 2 o 3

$Region$: 1, 2, or 3, area location in the visual FOV based on (Inanici 2005a)

CEM EI (19/10/2009, cloudy sky):

Court B1: 1:01 pm		Potential Glare Sourcess >(7x)			**112**
Region		L In situ (1)	L HDRI (2)	Contrast ratio: target(1)	Contrast ratio: target(2)
1	Target (2º)	14	16	-	-
2	Ceiling		34	-	2,1
2	Glazing area lateral window	1.775	1.830	110,9	114,4
2	Side Wall- orange	25	29	-	1,8
2	Floor	42	59	2,6	3,7
3	**Glazing area lateral window***	2.431	2.400	151,9	150,0
3	Glazing area skylight	1.823	2.290	113,9	143,1

* Calibration value

Frames	L max	L min	Contrast ratio:
Skylight opening/ adjacent ceiling	1.823	34	53,6
Windows opening/ adjacent ceiling	1.775	14	126,8

Table 5-2. Luminance contrast for spectator / remote spectator and television broadcasting - TV user in CEM EI building: B1 view direction.

Luminance values >112,0 cd/m² could be potential G_{source}, maximum contrast found by windows in region 2, 3.

CEM EI building: athlete view directions

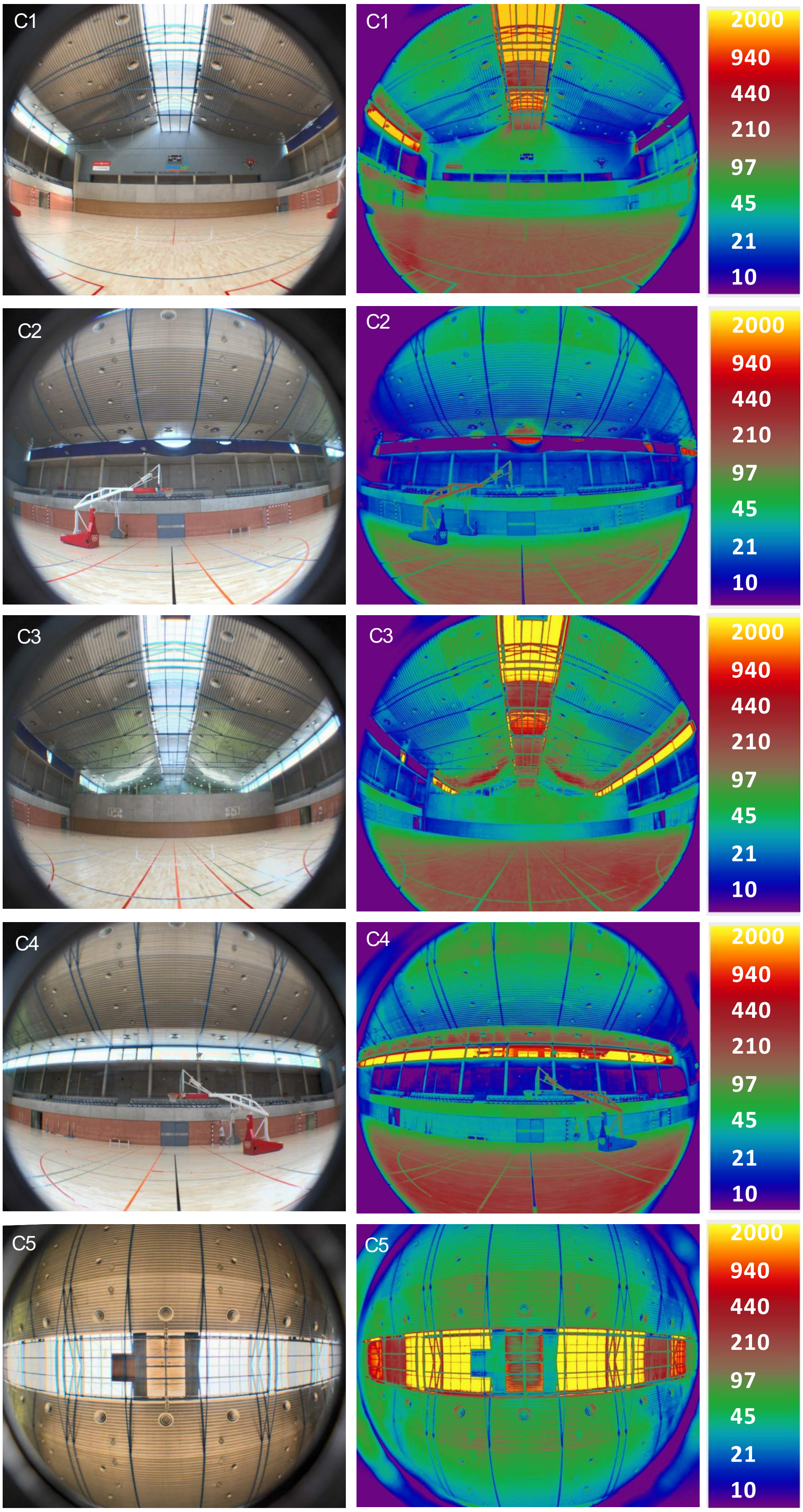

Figure 5-27. HDR images of CEM EI building: athlete view directions with False Colour Analysis (10-2.000 cd/m^2).

CEM EI (19/10/2009, cloudy sky): C1: 12:05 pm, C2: 12:28 pm, C3: 12:24 pm, C4: 12:13 pm, C5: 12:18 pm

CEM EI building: spectator /remote spectator and television broadcasting - TV view directions

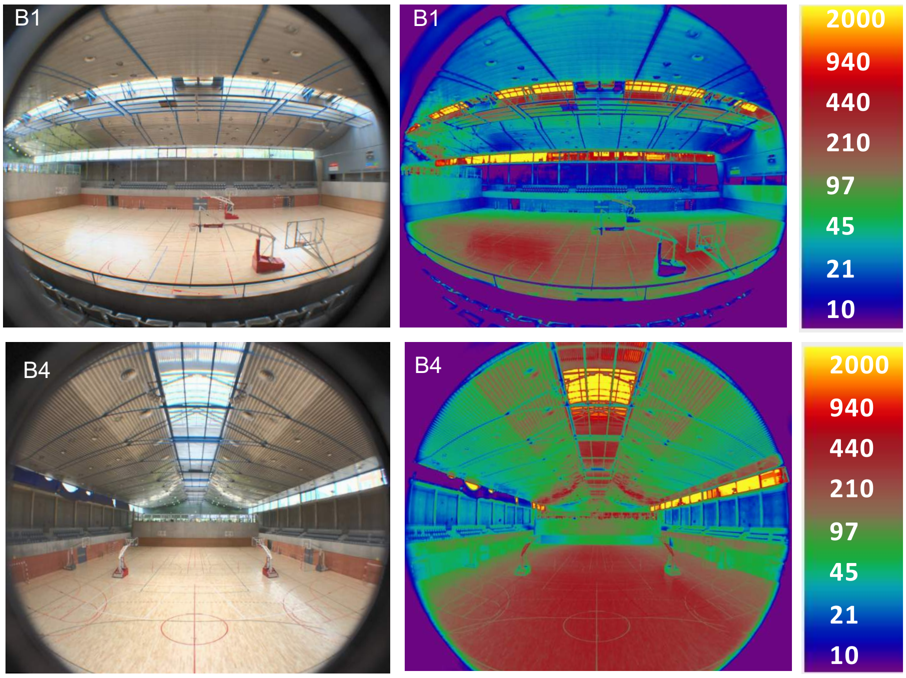

Figure 5-28. HDR images of CEM EI building: spectator view directions with False Colour Analysis (10-2.000 cd/m^2).

CEM EI (19/10/2009, cloudy sky), B1: 1:01 pm, B4: 1:15 pm

CEM EI building: glare and contrast quantification

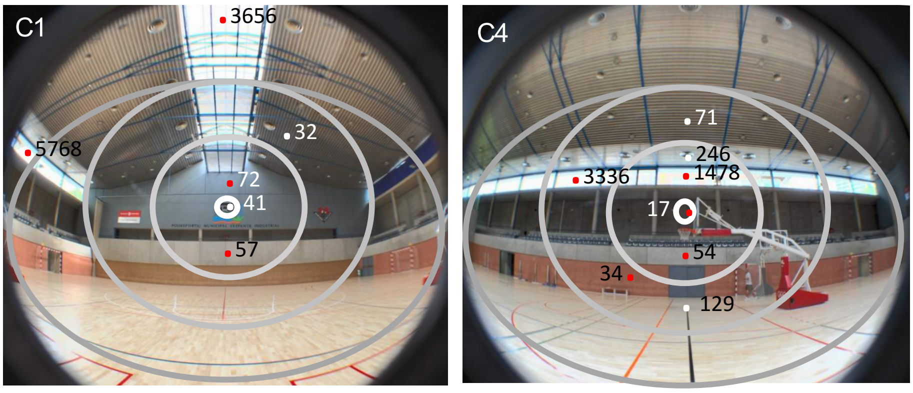

Figure 5-29. HDR images of CEM EI building: maximum L values (cd/m^2) obtained for athlete user.

CEM EI (19/10/2009, cloudy sky): C1: 12:05 pm L_{max}= 5768, C4: 12:13 pm L_{max}= 3336

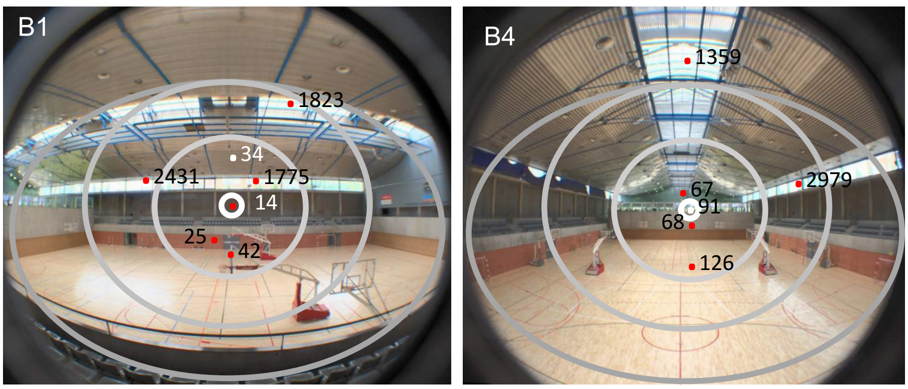

Figure 5-30. HDR images of CEM EI building: maximum L values (cd/m^2) obtained for spectator / remote spectator and television broadcasting - TV user.

CEM EI (19/10/2009, cloudy sky): B1: 1:01 pm L_{max}= 2431, B4: 1:15 pm L_{max}= 2979

5.2.2 Centre Esportiu Municipal Vall d'Hebron - CEM VH building

Athlete user

The maximum values of glare sources G_{source}, identified are from the North facing roof and windows. Depending on the view direction, it can be in the foveal and near surrounding regions, as shown in C3 and C5 view directions, see Figure 5-31 and Figure 5-33. The view of toplighting openings is not frequent, because they are generally in the peripheral region or background of the FOV.

Adaptation glare could be more frequent due to excessive contrast by hard frames from windows, see Table 5-3. Skylights could be sources of adaptation glare, but commonly placed out of the central areas 1 and 2 or in the peripheral area.

CEM VH (15/10/2009, intermediate sky)

Court C3: 11:59 pm — Potential Glare Sources >(7x) **119**

Region		L In situ (1)	L HDRI (2)	Contrast ratio: target(1)	Contrast ratio: target(2)
1	Target (2º)		17	-	-
2	Ceiling		16	-	0,9
2	Back wall		9		1,9
2	Bleachers	3	22	5,7	1,3
2	Glazing area lateral window*	430	429	25,3	25,2
3	Skylights wells	16	67	1,1	3,9
3	Side Wall		25		1,5
3	**Skylights opening***	**839**	844	49,4	49,6
3	Floor		21		1,2
3	Artificial light	23.220	938	1.365,9	55,2

* Calibration value

Frames	L max	L min	Contrast ratio:
Skylight opening/ adjacent ceiling	839	16	52,4
Windows opening/ adjacent wall	430	9	47,8

Table 5-3. Luminance contrast for athlete user in CEM VH building: C3 view direction.

Luminance values >119,0 cd/m² could be potential G_{source}, maximum contrast found by windows in region 2 and skylight in region 3.

Spectator / remote spectator and television broadcasting - TV user

The maximum luminance values found for spectators are from windows, as shown in B1 and Table 5-4. There are also veiling reflections on the floor from the windows when the blinds are partially operated, but in the peripheral area of FOV, see *Figure 5*-32 and Figure 5-34.

Adaptation glare could be very frequent due to excessive contrast by hard frames between windows and adjacent walls/ceiling, but commonly placed in the in the peripheral area of FOV.

CEM VH (07/10/2009, clear sky)

Bleachers B1: 12:27 pm — Potential Glare Sources >(7x) **84**

Region		L In situ (1)	L HDRI (2)	Contrast ratio: target(1)	Contrast ratio: target(2)
1	Target (2º)	1	12	-	-
2	Back wall	1	12	1,0	1,0
2	Ceiling	4	75	0,3	6,3
2	Basket Goal		52	-	4,3
2	Floor	1	25	1,0	2,1
	Glazing area lateral window*	**1.328**	1.320	1.328,0	110,0

* Calibration value

Frames	L max	L min	Contrast ratio:
Skylight opening/ adjacent ceiling	-	-	-
Windows opening/ adjacent ceiling	1.328	1	1.328,0

Table 5-4. Luminance contrast for spectator / remote spectator and television broadcasting - TV user in CEM VH building: B1 view direction.

Luminance values >84,0 cd/m² could be potential G_{source}, maximum contrast found by windows in region 3.

CEM VH building: athlete view directions

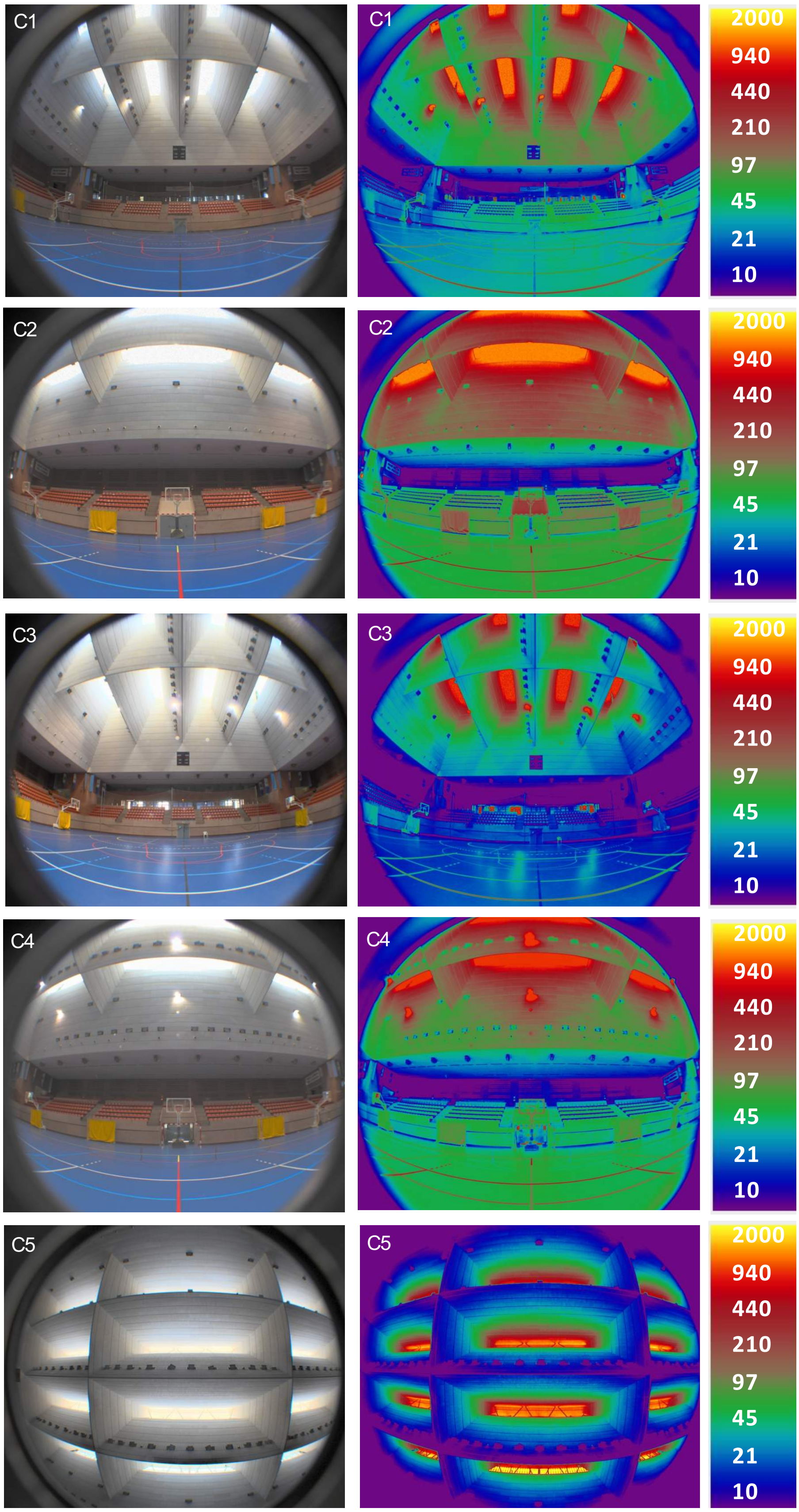

Figure 5-31. HDR images of CEM VH building: athlete view directions with False Colour Analysis (10-2.000 cd/m²).

CEM VH (15/10/2009, intermediate sky) C1: 12:10 pm, C2: 11:52 pm, C3: 11:59 pm, C4: 11:56 pm, C5: 12:31

CEM VH building: spectator/remote spectator and television broadcasting - TV view directions

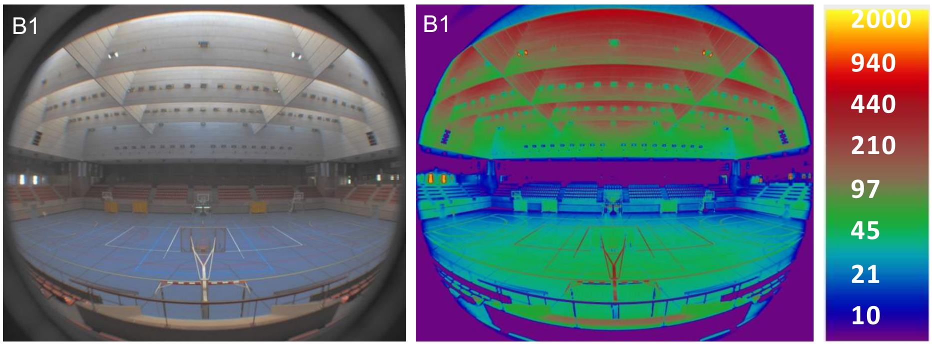

Figure 5-32. HDR images of CEM VH building: spectator / remote spectator and television broadcasting - TV view directions with False Colour Analysis (10-2.000 cd/m^2).

CEM VH (07/10/2009, clear sky) B1: 12:27 pm

CEM VH building: glare and contrast quantification

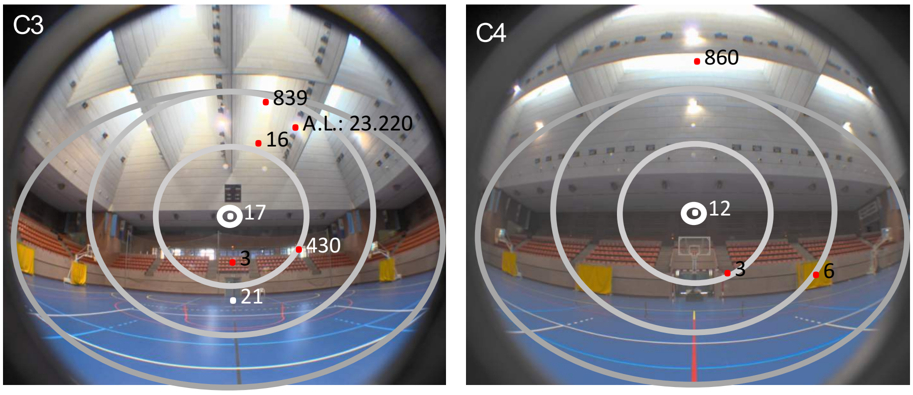

Figure 5-33. HDR images of CEM VH building: maximum L values (cd/m^2) obtained for athlete user.

CEM VH (15/10/2009, intermediate sky) C3- 11:59 pm: L_{max}= 839 from skylight well and 23.220 from artificial light, C4- 11:56 pm: L_{max}= 860 from skylight well

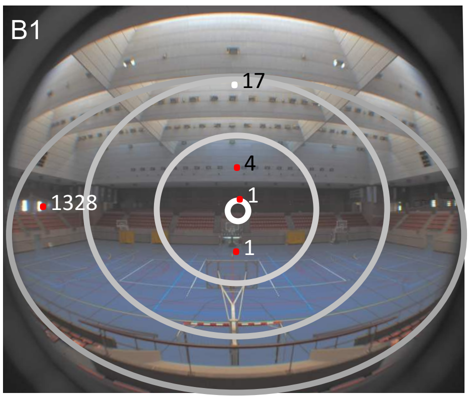

Figure 5-34. HDR images of CEM VH building: maximum L values (cd/m^2) obtained for spectator / remote spectator and television broadcasting - TV user.

CEM VH (07/10/2009, clear sky) B1-12:27 pm: L_{max}= 1.328 from lateral window

5.2.3 Institut Nacional d'Educació Física de Catalunya Montjuïc - INEFC building

Athlete user

The glare sources G_{source} with maximum values identified are from the side windows, in the near surrounding area the FOV, see Table 5-5. Depending on the view direction, it can be in the foveal region, as shown in C1, C2, C3 view directions.

In other viewpoints, there are potential glare sources of direct light from the side windows, but in peripheral situation, as in C4 see Figure 5-35 and Figure 5-37.

In the second place, the potential glare sources are the skylights, especially when the translucent surfaces allow the vision of the sky, but generally positioned in the peripheral region or background of the FOV.

There is a risk of adaptation glare in the central area of the FOV due to excessive contrast between windows and adjacent walls, e.g.: contrast ratio=33:1 in C2. High contrast between skylights and ceiling is also a potential source of adaptation glare, but commonly placed out of the mainly in the peripheral area, except when the gaze is towards the ceiling, as in C5.

INEFC M (5/11/2009, clear sky):
Court C2: 3:03 pm — Potential Glare Sources >(7x) **287**

Region		L In situ (1)	L HDRI (2)	Contrast ratio: target(1)	Contrast ratio: target(2)
1	Target (2º)		41	-	-
2	Ceiling		33	-	1,2
2	Glazing area skylights (near area)	290	408	7,1	10,0
2	**Glazing area lateral window***	**1.668**	1.690	40,7	41,2
3	Side Wall	50	24	1,2	1,7
	Glazing area skylight	599	439	14,6	10,7
	Floor		43	-	1,0
	Floor (reflection)		440	-	10,7

* Calibration value

Frames	L max	L min	Contrast ratio:
Skylight opening/ adjacent ceiling	599	33	18,2
Windows opening/ adjacent wall	1.668	50	33,4

Table 5-5. Luminance contrast for athlete user in INEFC building: C2 view direction.

Luminance values > 287,0 cd/m^2 could be potential G_{source}, maximum contrast found by windows in region 2.

Where:

$Potential\ Glare\ Sources > (7x)$: threshold obtained multiplying the luminance average value of the task L_{task} or target by 7 times

L_{task}: luminance of the target (2º) or task (cd/m^2)

$L\ in\ situ$ (1): luminance value obtained from in situ spot measurements (cd/m^2)

$L\ HDRI$ (2): luminance value of interior surfaces obtained from HDR images, after calibration process by PHOTOSPHERE software (Ward 2014, Version 1.8.16U) (cd/m^2)

$Contrast\ ratio$: $(target\ 1)$: ratio between the target against L in situ (1) values, from architectonic elements located in regions 2 or 3

$Contrast\ ratio\ (target\ 2)$: ratio between the target against L HDRI (2) values, from architectonic elements, located in regions 2 o 3

$Region$: 1, 2, or 3, area location in the visual FOV based on (Inanici 2005a)

INEFC building: athlete view directions

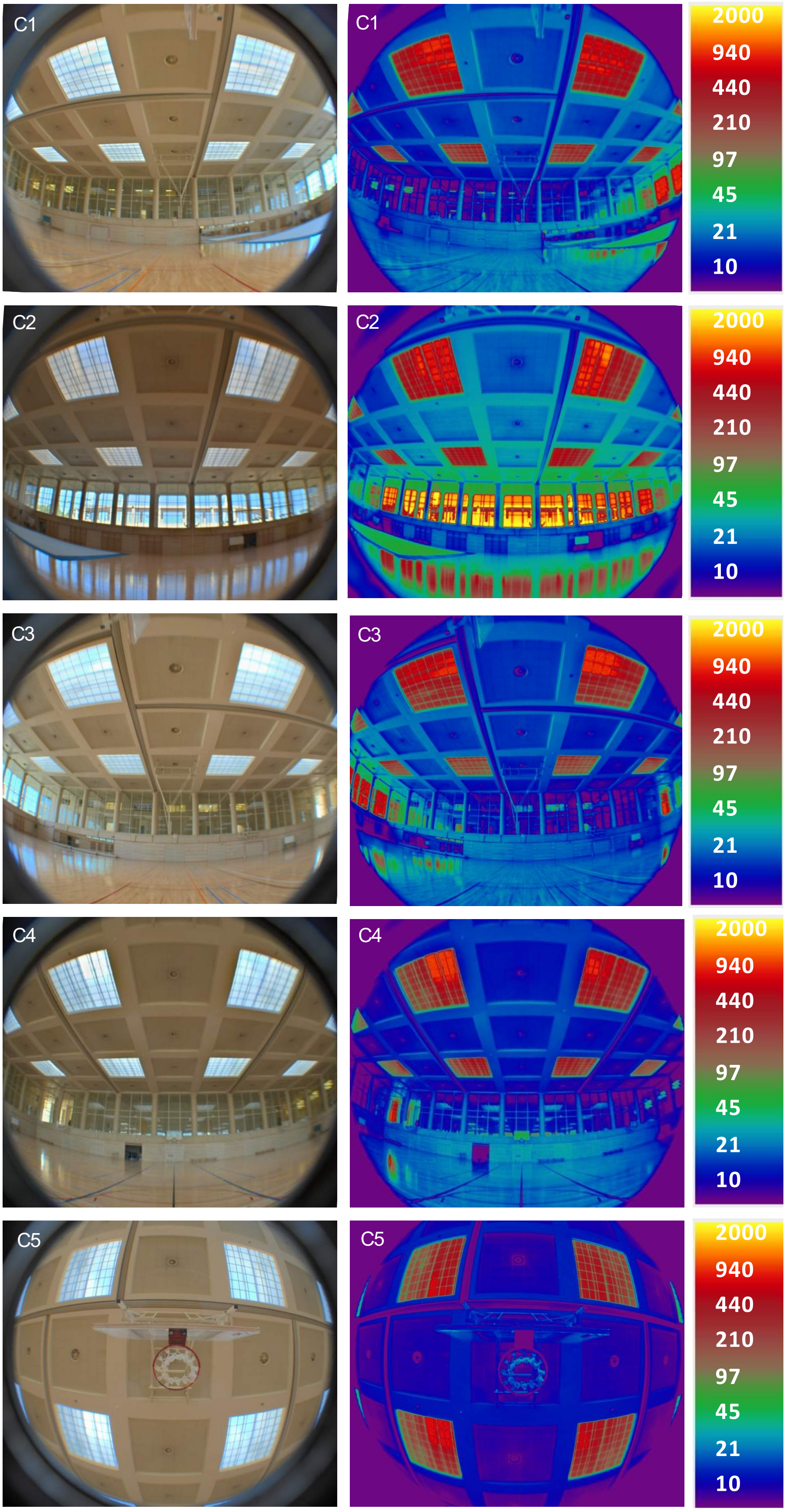

Figure 5-35. HDR images of INEFC building: athlete view directions with False Colour Analysis (10-2.000 cd/m²).

INEFC (5/11/2009, clear sky): C1: 3:01 pm, C2: 3:03 pm, C3: 3:10 pm, C4: 3:16 pm and C5: 3:32 pm

Spectator / remote spectator and television broadcasting - TV user

The potential glare sources for spectators are from window openings in the target and near surrounding areas, mostly when users are facing them, see Figure 5-6.

Windows are also a source of veiling reflections on the floor, although the blinds are partially down, see Figure 5-36 and Figure 5-38. There is a risk of adaptation glare in the central area of the FOV due to excessive contrast between windows and adjacent ceiling/walls, see B4.

INEFC M (5/11/2009, clear sky):

Bleachers B3: 3:54 Potential Glare Sources >(7x) **1505**

Region		L In situ (1)	L HDRI (2)	Contrast ratio: target(1)	Contrast ratio: target(2)
1	Target (2º)		215	-	-
2	Ceiling		17	-	12,6
2	Glazing area lateral window *	413	413	1,9	1,9
2	Glazing area skylights (near area)		78	-	2,8
2	Basket Goal/ Side Wall		10	-	21,5
2	Floor	10	13	21,5	16,5
3	Floor (light blue)	24	24	9,0	9,0
3	Floor (reflections)	128	127	1,7	1,7
3	**Glazing area lateral window**	**983**	428	4,6	2,0
	Glazing area skylight	98	98	2,2	2,2

* Calibration value

Frames	L max	L min	Contrast ratio:
Skylight opening/ adjacent ceiling	98	17	5,8
Windows opening/ adjacent ceiling	413	17	24,3

Table 5-6. Luminance contrast for spectator / remote spectator and television broadcasting - TV user in INEFC building: B3 view direction.

Luminance values >1.505,0 cd/m^2 could be potential G_{source}, maximum contrast by reflections on the floor in region 2

Where:

$Potential\ Glare\ Sources > (7x)$: threshold obtained multiplying the luminance average value of the task L_{task} or target by 7 times

L_{task}: luminance of the target (2º) or task (cd/m^2)

$L\ in\ situ$ (1): luminance value obtained from in situ spot measurements (cd/m^2)

$L\ HDRI$ (2): luminance value of interior surfaces obtained from HDR images, after calibration process by PHOTOSPHERE software (Ward 2014, Version 1.8.16U) (cd/m^2)

$Contrast\ ratio$: $(target\ 1)$: ratio between the target against L in situ (1) values, from architectonic elements located in regions 2 or 3

$Contrast\ ratio\ (target\ 2)$: ratio between the target against L HDRI (2) values, from architectonic elements, located in regions 2 o 3

$Region$: 1, 2, or 3, area location in the visual FOV based on (Inanici 2005a)

INEFC building: spectator/remote spectator and television broadcasting - TV view directions

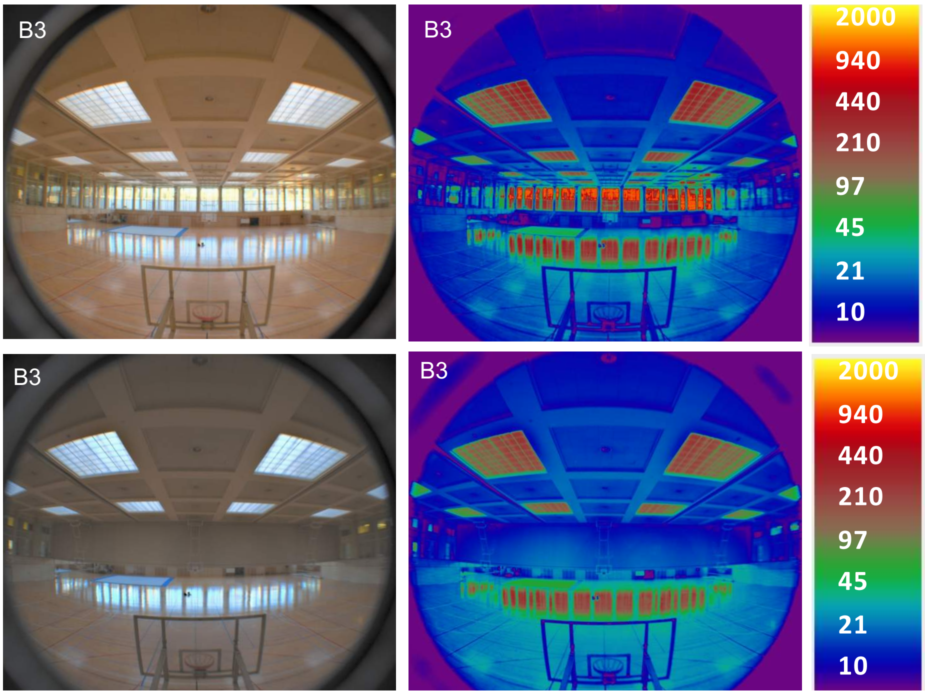

Figure 5-36. HDR images of INEFC building: spectator / remote spectator and television broadcasting - TV view directions with False Colour Analysis (10-2.000 cd/m²).

INEFC (5/11/2009, clear sky), B3: 3:54 pm, B3: 4:12 pm

INEFC building: glare and contrast quantification

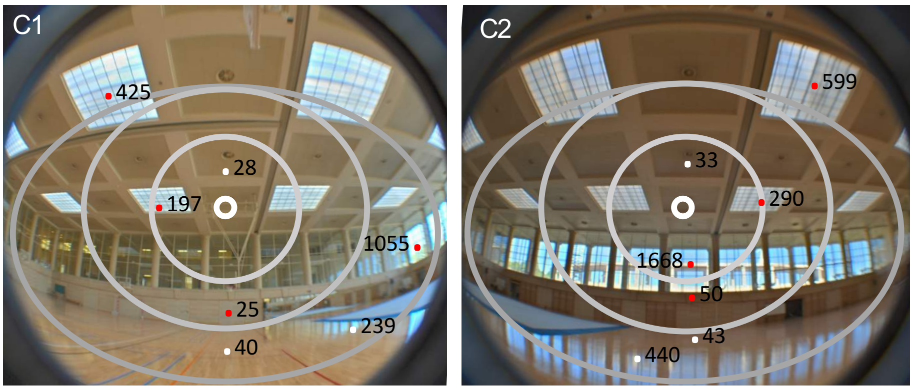

Figure 5-37. HDR images of INEFC building: maximum L values (cd/m²) obtained for athlete user.

INEFC (5/11/2009, clear sky): C1: 3:01 pm: L_{max}= 1.055 from lateral window, C2: 3:03 pm: L_{max}= 1.668 from window

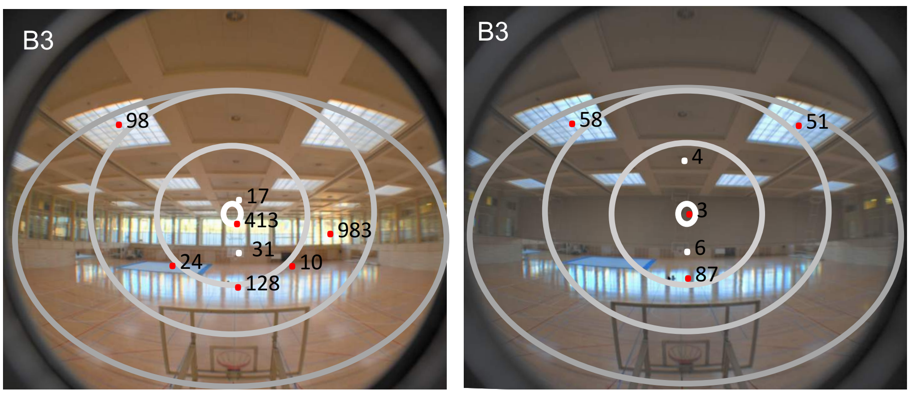

Figure 5-38. HDR images of INEFC building: maximum L values (cd/m²) obtained for spectator / remote spectator and television broadcasting - TV user.

INEFC (5/11/2009, clear sky), B3: 3:54 pm: L_{max}= 983 from window, B3: 4:12 pm: L_{max}= 87 from reflection on the floor

5.2.4 Palau d'Esports de Granollers - PEG building

Athlete user

The maximum values of glare sources G_{source} identified for athletes are from the side windows and access doors to the court, see C2 and Table 5-7. Depending on the viewing direction, these G_s can be located in the foveal or near surrounding areas, as shown in C2 and C3, see Figure 5-39 and Figure 5-41. In the second place, the vision of the skylight openings are sources of glare, as shown in C2, but frequently, in the peripheral region or out of the FOV, except when the gaze is towards the ceiling, C5. There is potential adaptation glare due to the excessive contrast between windows and back walls, see Table 5-7. There is also an excessive contrast between skylight wells and black stripes of ceiling, affecting the view direction towards the ceiling.

PEG (14/10/2009, clear sky):
Court C3: 2:27 pm — Potential Glare Sources >(7x) **1778**

Region		L In situ (1)	L HDRI (2)	Contrast ratio: target(1)	Contrast ratio: target(2)
1	Target (2º)		254	-	-
2	Side wall white	54	36	4,7	7,1
2	Side wall, back		4	-	63,5
2	Bleachers	6	14	42,3	18,1
2	Window 1		545	-	2,1
3	Skylight opening	582	585	0,4	2,3
3	Skyligt well		90		
3	Ceiling, black		2	-	127,0
3	Floor		30	-	8,5

* Calibration value

Frames	L max	L min	Contrast ratio:
Skylight opening/ adjacent ceiling	582	90	6,5
Windows opening/ adjacent wall	545	4	136,3

Table 5-7. Luminance contrast for athlete user in PEG building: C3 view direction.

Luminance values >1.778,0 cd/m^2 could be potential G_{source}, maximum contrast by bleachers and side walls in region 2, and ceiling in region 3.

Spectator / remote spectator and television broadcasting - TV user

The maximum values found of $G_{sources}$ for spectators are from the lateral windows, seen through the bleachers, see B1 and Table 5-8. In the second place, there are the skylight wells, but frequently in the peripheral region or background of the FOV, see Figure 5-40 and Figure 5-42. There is a low risk of adaptation glare due to the excessive contrast between windows and bleachers, and between skylight wells and the black ceiling stripes.

PEG (14/10/2009, clear sky):
Bleachers B1: 1:40 pm — Potential Glare Sources >(7x) **420**

Region		L In situ (1)	L HDRI (2)	Contrast ratio: target(1)	Contrast ratio: target(2)
1	Target (2º)		60	-	-
2	Skyligt well*	73	70	1,2	1,2
2	Ceiling, black	6	3	10,0	20,0
2	Floor, grey	11	11	5,5	5,5
2	Blind	66	69	1,1	1,2
2	Bleachers		17	-	3,5
2	**Windows, back**		**220**	-	3,7
3	Floor, red		22	-	2,7
3	Floor, wood		53	-	1,1

* Calibration value

Frames	L max	L min	Contrast ratio:
Skylight well/ adjacent ceiling	73	6	12,2
Windows opening/ adjacent ceiling	220	17	12,9

Table 5-8. Luminance contrast for spectator / remote spectator and television broadcasting - TV user in PEG building: B1 view direction.

Luminance values >420,0 cd/m^2 could be potential G_{source}, maximum contrast by windows in region 2.

PEG building: athlete view directions

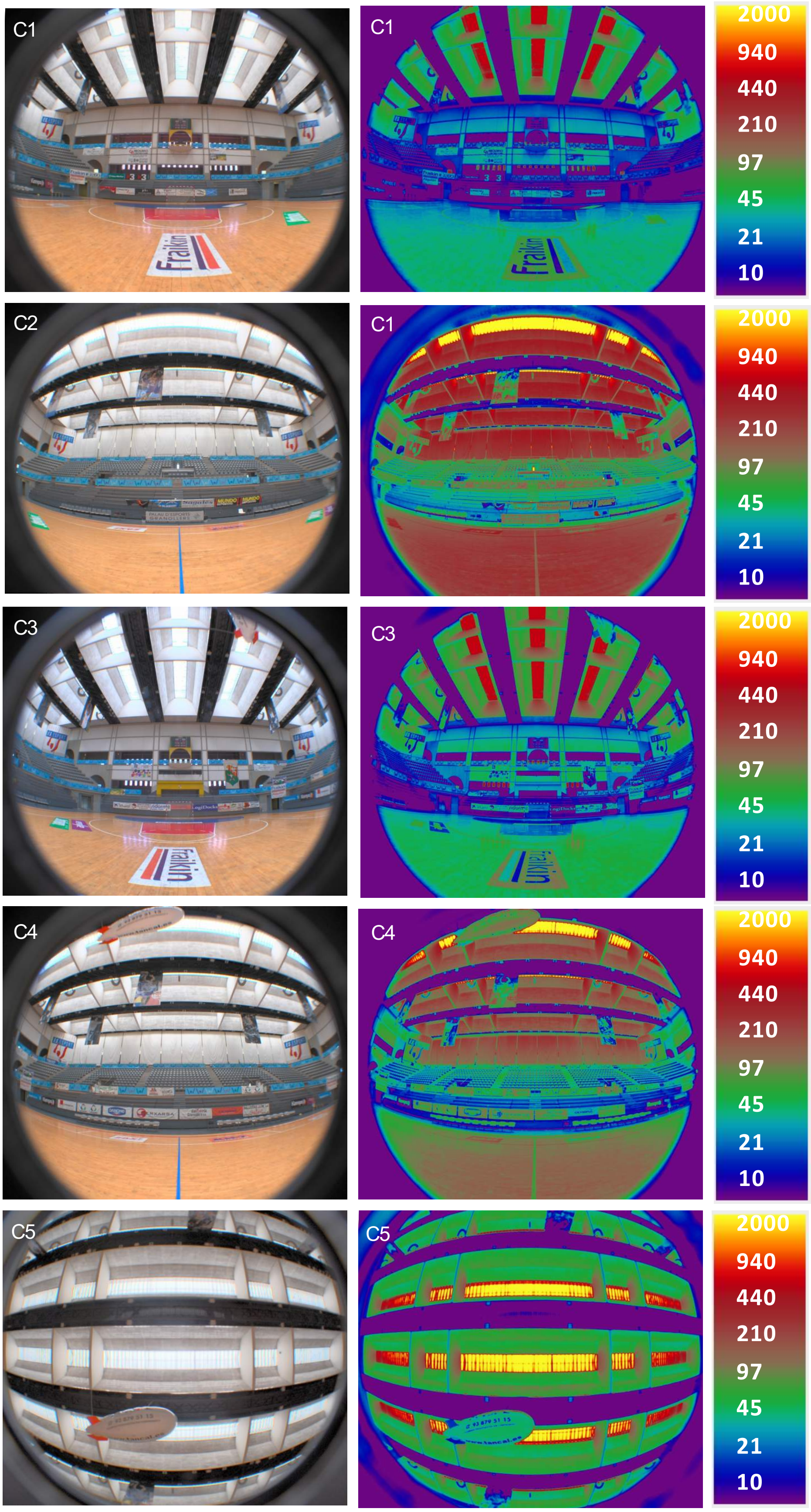

Figure 5-39 HDR images of PEG building: athlete view directions with False Colour Analysis (10-2.000 cd/m²).

PEG (14/10/2009, clear sky): C1: 2:17 pm, C2: 2:21 pm, C3: 2:27 pm, C4: 2:32 pm and C5: 2:40 pm

PEG building: spectator/remote spectator and television broadcasting - TV view direction

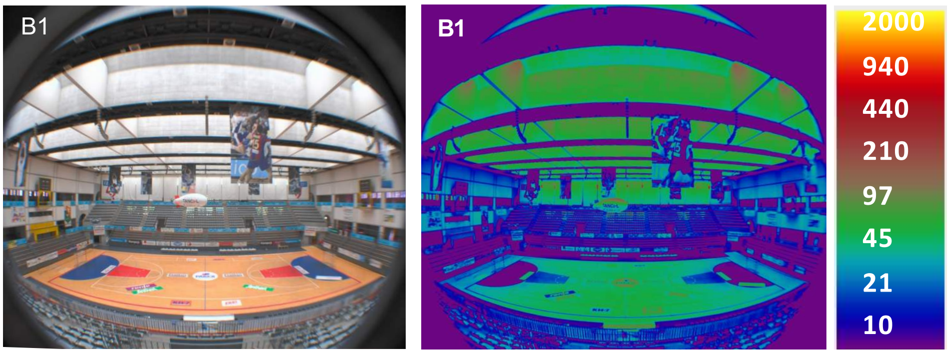

Figure 5-40. HDR images of PEG building: spectator / remote spectator and television broadcasting - TV view directions with False Colour Analysis (10-2.000 cd/m^2).

PEG (14/10/2009, clear sky): B1: 1:40 pm

PEG building: glare and contrast quantification

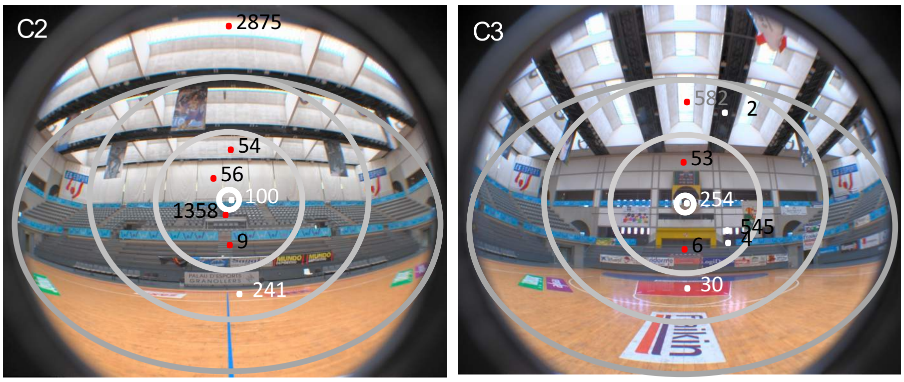

Figure 5-41. HDR images of PEG building: maximum L values (cd/m^2) obtained for athlete user.

PEG (14/10/2009, clear sky): C2: 2:21 pm, C3: 2:27 pm

Figure 5-42. HDR images of PEG building: maximum L values (cd/m^2) obtained spectator / remote spectator and television broadcasting - TV user.

PEG (14/10/2009, clear sky): B1: 1:40 pm

5.3 Discussion of results

5.3.1 Visual comfort in the reference sample

There are several factors of the day-lit environment that can affect users' visual comfort in sports halls. The most frequent situations found in the case studies of the reference sample and linked with the visual discomfort of sports halls users are the following:

- Inadequate horizontal illuminance - E_h levels or quantity of light/ daylight in the court during daytime, to perform the sports activities
- Lack of horizontal illuminance uniformity – U in the court/playing area
- Discomfort glare and disability glare by:
  - Glare sources: related to their position in the scene and the interaction between users and luminous environment
  - Lack of control and shading devices: direct and diffuse light
  - Adaptation level and unsuitable luminance distribution in the users' field of view - FOV
  - Overall perception of the luminous scene: dark and gloomy

Horizontal illuminance - E_h levels in the court

Related to the quantity of daylight, the results show that in the majority of case studies measured (70%) a minimum level of illuminance in the court was verified for training conditions ($E_{h\ ave}$ > 200 - 300lx in seven sports halls out of ten), including E_h for competition conditions in four buildings (E_h> 300 - 500lx).

However, three case studies have been found where the minimum E_h levels for training conditions are not achieved ($E_{h\ ave}$ < 150lx). In these cases, the visual comfort could be affected when there is not enough lighting level on the court. Therefore, the artificial lighting could be necessary during daytime, for training and/or competition level of play, according to the case.

Daylight factor on the court- DF%

In the majority of case studies (60%) where DF% were obtained, a minim level of DF 1,5% was verified for training conditions (three out of five buildings). In the case of a competitive level of play, the addition of artificial light could be likely necessary.

Two case studies have been found where the DF% is below <1%. In these situations, the level of daylight could be unsuitable or too low for training conditions, in the first place, and subsequently for competition conditions, requiring the addition of artificial light during daytime.

Uniformity on the court- U

A minimum of horizontal illuminance uniformity on the court was verified in the majority (70%) of case studies: three case studies (U > 0,4 - 0,5) and in four (U > 0,5).

Three sports halls have been found where the minimum U is not achieved (U < 0,4) due to mainly the contribution of direct light from the side windows. In some cases, it was also due to toplighting systems. The areas of the court near the windows have high levels of light due to their proximity. As a result, the court surface shows dark and bright areas.

Glare sources - Gs in the court

The most common direct and indirect sources of glare in the court found in existing sports halls of the reference sample are the following:

- Direct light or sunlight penetration in the court and seating areas, in first place by sidelighting (23%) and by toplighting systems (17%), in second place
- Reflections on interior surfaces: on the court surface by sidelighting (69%)
- External reflections and view of the sky through the windows (61%)
- The view of daylight openings or glazing areas of windows, in first place (92%), and toplighting openings (50%), in second place

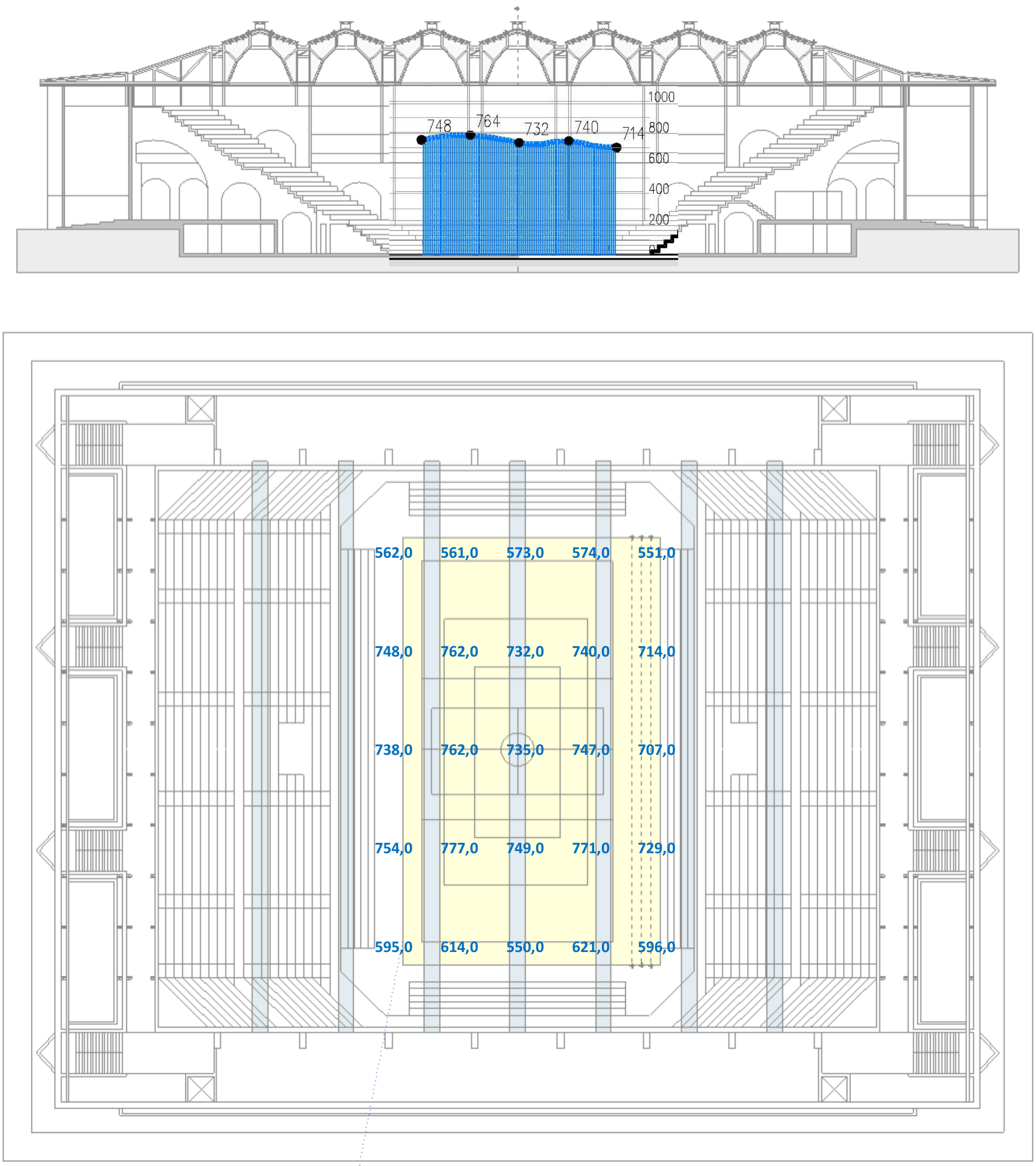

Figure 5-43. Graphics of illuminance levels measured in the court: the PEG building.

PEG (23/01/2008 12:50 pm, clear sky) $E_{h\ ave}$=729 lx

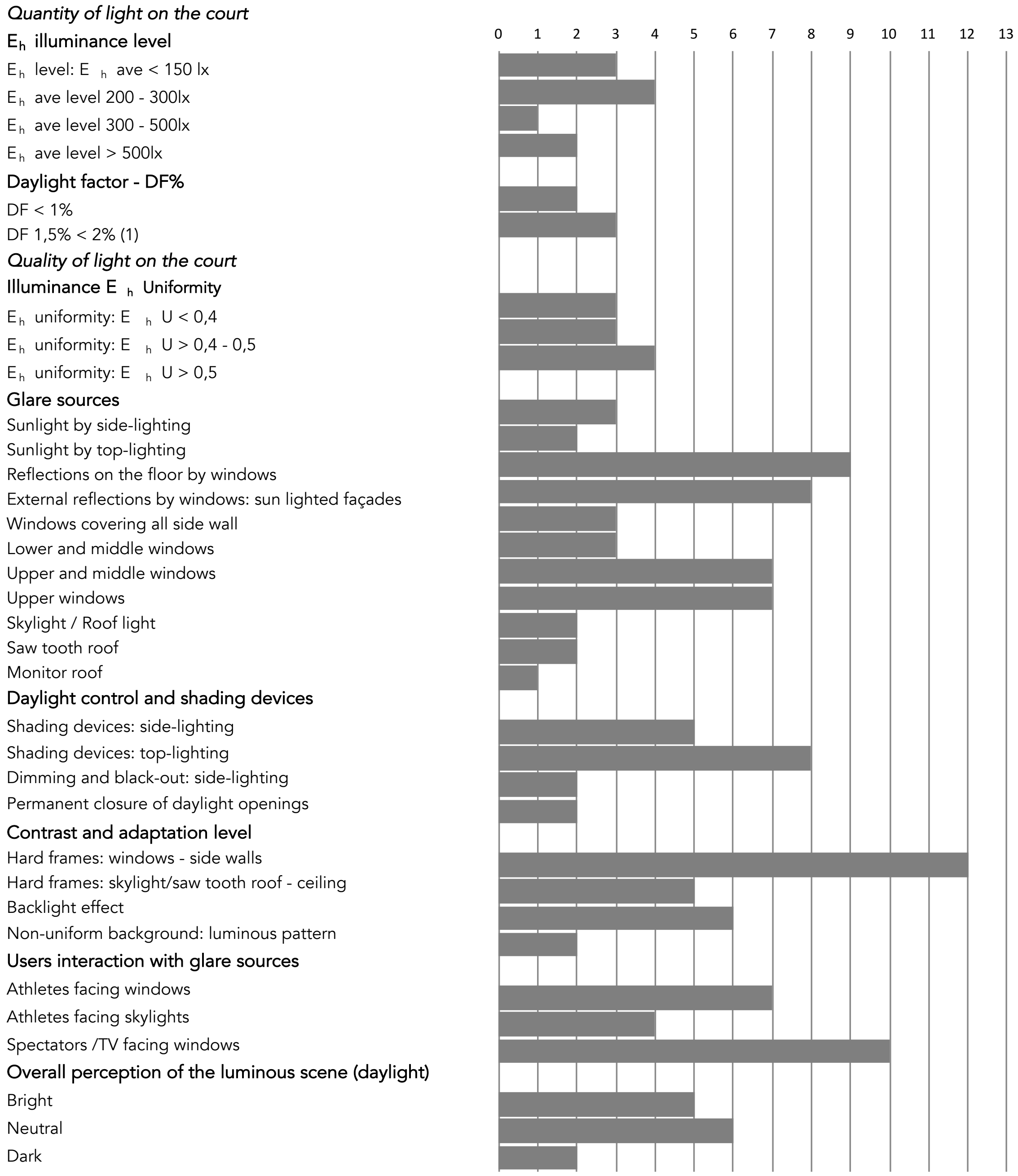

Table 5-9. Summary of the results of the quantitative and qualitative assessment on the court, carried out in 13 buildings of the reference sample: site visits and monitoring campaigns.

Excessive contrast and adaptation level

In the majority of case studies adaptation or relative glare situations could happen due to an excessive contrast of luminances in the users' FOV. The difficulty in the eye's adaptation is not caused by an absolute value, but relative when users are tracking visual targets in the space and in short periods of time.

The most frequent discomfort situations by adaptation found in case studies are the following:

- Hard frames: mostly between windows and side walls were found in the majority of case studies (92%), skylights and ceiling (42%), accentuated by contrasting openings over dark and not well day-lit opaque surfaces
- Backlight effect by sidelighting (41%)
- Non-uniform backgrounds or brightness patterns due to dissimilar reflectance values when users are looking towards frequent view directions

Users interaction with the luminous environment

The potential discomfort glare situations could increase their intensity and occurrence when the users are facing openings of sidelighting and toplighting systems. This is because the user position in the space and main view directions are not static with respect to the location of glare sources.

Luminous environment: overall perception

In terms of internal reflectance values, the results show that the majority of case studies (46%) have medium reflectance values on architectonic surfaces, followed by the bright values (39%) and low values (15%). In the majority of case studies with subjective neutral or dark perception of the scene, medium and low reflectance coefficients have been found frequently in floors and side walls.

The combination of many factors could contribute to the overall perception of the luminous scene. The results suggest these main factors are the following:

- Horizontal illuminance - E_h levels in the court
- Reflectance coefficients, mainly on the court surface (floor), sidewalls and ceiling surfaces
- Daylight hitting and reflected by side walls and ceilings

Additionally, the diffuse light from the sky dome by toplighting systems could accentuate the "cold light" appearance after several internal reflections. This could give observers a global perception of a dark and gloomy environment. As a consequence, the use of artificial light could be required during the daytime, despite the fact that daylight levels could be suitable for training conditions.

5.3.2 Visual comfort in the final sample

The potential and existing situations of visual discomfort and disability glare found in the final sample are presented according to absolute glare values, glare sources in the visual field for users and adaptation glare by hard frames.

Absolute glare

Frequent and potential absolute glare sources (L>2.000 cd/m^2) were identified in the FOV of athletes, spectators and TV broadcasting due to following situations:

- Sunlight or direct light from windows
- View of glazing areas of sidelighting and toplighting systems
- Reflections on the court surface from windows

Glare sources -G_{source}

The maximum luminance values L_{Max} of glare sources G_{source} found in the case studies (<2.000 cd/m^2) are from sidelighting systems, in particular from windows.

Likewise, they are more likely to be the potential glare sources G_{source} and cause discomfort and disability glare situations because of their relative position in the foveal and near surrounding areas of the user's FOV. The critical situations in the central area of the FOV and with maximum luminance values L_{max} are when users are facing windows. The risk of discomfort and disability glare in the athletes FOV from G_{source} glare sources are highly probable from sunlight, direct and reflected light from outdoor elements and reflections on the court surface.

In the second place, the view of glazing areas of skylights are considered potential glare sources. However, toplighting systems are commonly placed in the peripheral area of the users' FOV during the visual task. View directions facing to them and to the ceiling are less frequent, considering the type of sports and sports activities.

Adaptation glare

Excessive contrast situations were found due to hard frames between:

- Glazing and opaque surfaces, most frequently in the central area of the FOV, from windows and adjacent walls. In second place from skylights and adjacent ceiling
- Dissimilar reflectance factors and colours in adjacent surfaces

Potential adaptation glare situations have been found mostly by windows, with a contrast of >33:1 in the area 2, and >130:1 in the area 3. Hard frames and excessive contrast in adjacent surfaces due to dissimilar reflectance values and the light hitting the surfaces, could cause more frequent discomfort situations.

5.4 Chapter conclusions

The performance of day-lit sports halls was analysed through in-situ measurements and comprehensive surveys, carried out in the reference and final sample to obtain horizontal E_h and vertical illuminance E_v, Daylight Factor - DF% and Uniformity – U. Likewise, static numerical simulations were performed to widen the data acquisition from real case studies.

In order to identify and quantify glare sources $G_{sources}$ with calibrated luminance maps, a detailed assessment of the users' Field of View - FOV in the final sample was also performed. High dynamic range images - HDRI surveys and spot measurements of luminance - L were obtained in the main view directions for each user.

Although the measurements were not carried out in an extensive sample, these results are significant for the main hypothesis, in terms of objective and subjective data and providing quantitative and qualitative assessment of day-lit in–use sports hall buildings in Catalunya.

Global performance of daylighting and toplighting

Minimum levels of horizontal illuminance - E_h, uniformity - U, and daylight factor - DF% for training conditions on the court have been verified in the majority of case studies by daylight and without the contribution of artificial light. Moreover, in four examples minimum levels of daylighting were also verified for competitions. However, unsuitable or too low illuminance levels in the court were verified for training activities, in the case of North facing roof lights and North facing monitor roofs, for example in CEM VH and PEGF buildings.

Likewise, low risk of existing and potential glare and adaptation level situations in the users' FOV were found by toplighting systems.

Existing and potential discomfort situations for sports hall's users, athletes, spectators and remote spectators/TV broadcasting were identified according to the following:

- Low horizontal illuminance E_h levels and lack of illuminance uniformity U on the court
- Absolute glare and discomfort glare situations due to glare sources in the FOV, mostly from sidelighting systems
- Lack or insufficient control of daylight and shading devices
- Discomfort glare by adaptation level and lack of luminance L uniformity in the FOV, mostly from sidelighting systems
- Dark or neutral perception of the luminous environment due to reflectance values on interior architectonic surfaces

Low horizontal illuminance level

Toplighting systems oriented to North could result in poor daylight levels in the court to perform training activities, mainly because of small openings exposed to the sky vault and exclusive contribution by diffuse light. Consequently, this could lead to the permanent use of artificial light for training and competition levels of play during the day.

Lack of illuminance uniformity

The majority of the case studies with mainly toplighting systems have an acceptable level of uniformity in the court. Moreover, the dissimilar distribution of daylighting levels on the court are due mostly to the contribution of sunlight or direct light by sidelighting and toplighting systems, with insufficient or lack of solar control.

Glare sources

In the majority of the case studies, the view of sidelighting systems in the court and seating areas are the most likely direct and indirect sources of glare in the field of view - FOV. It could be due to the side windows are commonly placed in the centre of the users' FOV, nearby to the target when users are performing the visual task. The risk of discomfort and disability glare in the athletes FOV from G_{source} glare sources is highly probable from sunlight, direct and reflected light from outdoor elements and reflections on the court surface by windows.

The view of glazing areas of skylights is also considered as a potential glare source, although toplighting systems are commonly placed in the peripheral area of the users' FOV during visual tasks. Furthermore, views towards the ceiling and toplighting openings are less frequent than windows, considering the type of sport and common sports activities.

User position and view-directions

Related to the users' position in the space, the results suggest that critical situations occur when the openings are in the centre of the FOV of athletes, spectators and TV cameras. These situations are likely to be related to windows covering all, lower and middle parts of the side and back walls. In contrast, these potential glare situations are less critical when the openings are in the upper part of the line of vision, as clerestories and toplighting openings. Skylights and saw tooth roofs also result to be in the peripheral area of the users' FOV and consistent with less sensitive region of the FOV. In addition, this could be also explained in relation to frequent view directions, in particular to the athlete, which is the most dynamic user in the sports hall space.

Considering the position of the glare sources in the space, the results show that there is a high risk of discomfort and even disability glare when the users are facing windows or the gaze is towards them. The quantification of luminances by the detailed visual comfort assessment is consistent with these results.

However, the analysis of luminances was performed considering a fixed target in the central area of the FOV. Multiple targets could be essential for an extensive validation of these results, taking into account the dynamics of users and their visual task.

Adaptation level in the field of view - FOV

Situations of discomfort glare by adaptation level have been found in the majority of case studies due to the excessive contrast in the FOV by hard frames. The most frequent situations are: windows/side walls and skylights/ceiling, subjective brightness and backlight effect by windows. These situations could be critical in sports with dynamic users and moving targets, where changes in gaze, view direction and targets happen in a very short time.

This suggests that the lack of transition between adjacent surfaces with different luminance values (cd/m^2) is highly likely to generate discomfort or disability glare, especially from sidelighting systems. Dissimilar reflectance factors, different colours and different lighting distribution in adjacent horizontal and vertical surfaces are also likely to generate a non-uniform background to distinguish the moving target.

Overall perception of the luminous environment

The internal reflections perform an important role in the overall scene perception. The results suggest that the addition of saturated colours on the floor surfaces could noticeably modify the internal reflections and the visual perception of the overall space, for example due to competitions requirements. This may be explained by the direct correlation between the reflectance coefficients and colours or reflected light of the main elements in the FOV and the perception of the luminous environment.

Lack of daylight control and shading devices

Remarkably, the lack of daylight control devices to adjust, dimmer, and black-out the natural light were found in the majority of the case studies but few exceptions including blinds and louvers. Besides, many of the visual discomfort and disability glare situations described have their origin in the absence or insufficient regulation of natural light on the court.

The lack of these elements to control the natural light is the most likely cause of definitive closure, mainly for toplighting systems. Likewise, if this condition persists it can lead to the permanent use of artificial light during daytime in both training and competition activities.

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2nd Part - Assessment of daylighting design strategies to improve visual comfort in sports halls using simulations and experimental test

6

Design strategies and measures

The previous chapter discussed the preliminary results of the visual comfort assessment in the reference and final samples. Visual discomfort situations were identified for each user in the case studies. Based on these results, daylighting design strategies to improve visual comfort in sports halls are presented. Likewise, bespoke measures and variables for each sports hall of the final sample are suggested and developed in the second part.

The results of this chapter and the preceding Chapter 5 are the fundamentals for the design measures implemented in experimental tests, carried out at LASH - ENTPE (González Matterson, 2011), see Appendix IV, section A, pp. 2-53.

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6.1 Daylighting design strategies for the visual comfort

The aim of the design strategies is the improvement of the users' visual comfort by modifying situations where the users are experiencing existing or potential visual disability and/or discomfort.

Based on the assessment in existing sports halls described in the previous Chapter 5, design strategies are suggested to respond to visual comfort requirements, in training and competitive level of play. These users' visual requirements identified in the reference and final sample are explained in terms of quantity and quality of natural light, see Table 6-1.

6.1.1 Measures for the visual comfort: final sample

The design measures are specific modifications proposed to improve the building performance, in this work in particular, the visual comfort conditions.

Based on the daylighting design strategies, the measures provide new elements and/or the replacement of existing features in the architectonic space, considering the performance of daylighting systems and visual comfort.

These measures were proposed with the aim of being incorporated into virtual models of the final reference to be tested.

The selected measures included existing technologies and materials, see Appendix IV section A, pp. 14-17. The majority of them are passive and also frequent in basic building retrofitting and maintenance works. Examples of that are windows upgrading with replacement of frames and glazing materials, wall and ceiling painting and the addition of external and internal shading devices.

However, some measures can be considered as intrusive or hardly feasible due to their economic costs or structural and functional implications.

Tailored measures and variables

Different measures were proposed for the final sample case studies: CEM EI, CEM VH, INEFC and PEG buildings. Accordingly, the measures were tailored for each case study, according to the discomfort situations found in the visual comfort assessments. For this reason, not all the measures are implemented in the final sample. Measures variables were also customized individually for each of the four buildings. Each measure has variables that are proposed for a specific case study or more than one. The baseline scenario corresponds to the actual or real conditions of performance.

In the next points, the strategies will be explained and specified, see Table 6-1 for a complete detail of the measures and variables. Then, these measures and variables were simulated and tested by users, see Chapter 7.

6.2 Daylighting design strategies to modify the quantity of light

In terms of the quantity of light, the main requirement is to increase the E_h horizontal illuminance level in the playing area (+1,00 level) to meet the minimum targets, at least, for training conditions (300 lx horizontal illuminance level, or DF 2%) For that, the improvement of daylight admittance from toplighting systems is proposed.

Figure 6-1. Images showing the detail of the flat roof light and the suspended white vertical baffles in office building.

CIEM - Centro de Incubación Empresarial Milla Digital in Zaragoza, ES (García, J & Sánchez, A., 2011): (30/10/2013 12:23 pm, clear sky) detail view of the flat roof lights, aperture controls for natural ventilation and vertical white baffles from the access to the roof, left. View of the suspended ceiling from 3rd floor, right.

Figure 6-2. Images showing examples of sports halls, with surfaces integrated on the ceiling to redirect and diffusing daylight: white splayed intersections, baffles and louvres.

PMGF building (22/05/2007 1:15 pm, clear sky), left. CEM VH building (19/02/2008 1:00 pm, overcast sky), centre. PEG building (23/01/2008 12:50 pm, clear sky) right.

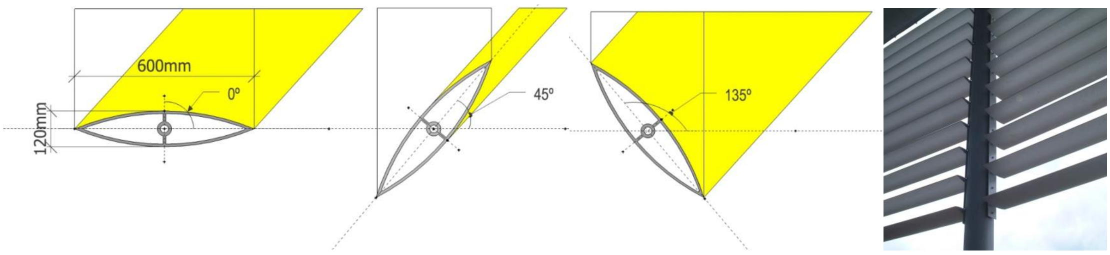

Figure 6-3. Detail of fixed louvres and schemes of different tilting angles proposed for shading devices.

External louvres disposition for windows:0°, internal disposition of louvres/baffles for roof lights 45° and 135°, left. Louvres appearance in horizontal position, right (Source: https://www.coltinfo.co.uk/colt-product-library/solar-shading/aluminium-louvre-solarfin/specification.html)

6.2.1 Increasing daylight admittance: roof light variations

The aim is admitting more natural light from toplighting systems, in particular by increasing the diffuse light from the sky dome. Effective solar shading devices are required to increase the illuminance level but preventing potential sunlight penetration in the playing area.

Skylight or roof light variations are proposed to maximize the diffuse daylight admittance that could contribute to increase the E_h horizontal illuminance levels and illuminance uniformity U on the court or playing area, according to:

- Increasing the sky dome aperture and the glazing area surface (width)
- Increasing the glazing light transmission factor

However, the addition of solar shading devices is required to avoid the risk of glare situations, see section 6.3.1.

A- Increasing sky dome aperture - θ

The replacement of the existing toplighting system with a flat roof light, increasing the sky dome angle or aperture, is proposed in two case studies, in the CEM EI and CEM VH buildings, see Figure 6-4.

B- Increasing glass transmission factor

The replacement of existing roof lights glazing area, increasing the glass transmission factor, is proposed in two cases studies: the CEM EI and CEM VH buildings.

6.3 Daylighting design strategies to modify the quality of light

The main requirements to improve the quality of light are to provide a suitable luminous environment for user's visual field, avoiding visual disability and discomfort situations, according to the following:

- Increasing the horizontal illuminance uniformity - U on the playing area
- Avoiding solar penetration in the playing and seating area by integrating shading devices
- Avoiding glare sources in the visual field by diffuse light, external reflections, veiling reflections on the floor
- Improving the luminance uniformity and reducing excessive contrast between the interior surfaces in the users' field of view – FOV or users' visual field

6.3.1 Integrating shading devices: obstructing, reflecting and redirecting sunlight

The main goal of integrating solar shading devices is to avoid direct light, from high and medium angles from the sun, and to control reflected sunlight from both external and internal surfaces in the court and tribunes.

In the same way, it is to reduce glare sources in the visual field by the incorporation of solar shading devices to prevent sunlight, external reflections and veiling reflections on the floor, especially in the playing area. Likewise, it is to contribute to the illuminances level and uniformity - U in the court and to increase the daylight admittance by transforming direct light into diffuse light.

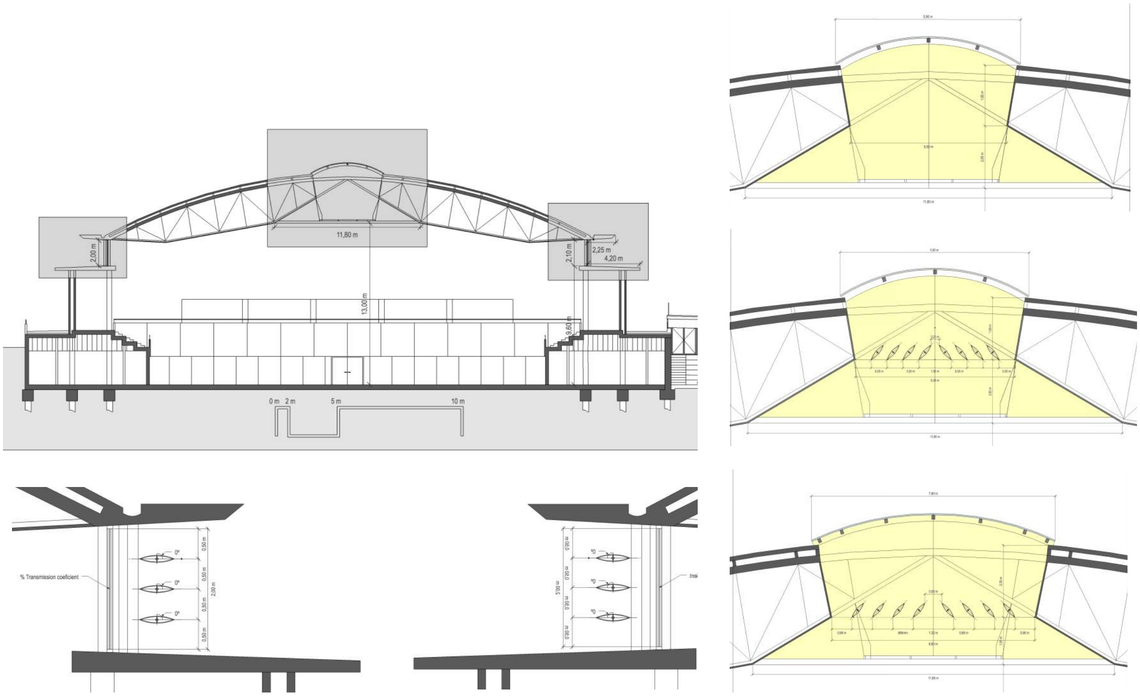

Figure 6-4. Cross section showing measures proposed for the CEM EI building.

CEM EI building: increasing the daylight admittance and integrating shading devices: exterior louvres (0°) in windows, left. Interior tilted louvres (45°+135°) in the roof light, right.

Figure 6-5. Rendered images showing measures proposed for the INEFC building.

The variables to reduce the glass transmission factor in side windows, (left to right): E-0: baseline Tv=0.85; E-1: Tv=0.60; E-2: Tv=0.40; E-3: Tv=0.20.

Figure 6-6. Rendered images showing measures proposed for the INEFC building.

INEFC building: addition of artificial light in the ceiling, left to right: HI-0: no artificial light, baseline; HI-3: bright squares L=250 cd/m^2; and HI-1: bright squares L=750 cd/m^2.

Louvres and baffles with different orientation angles are proposed to control, to re-direct and to diffuse sunlight, and also, to block external reflected light from the ground and surrounding buildings through the windows. Additionally, the use of interior white vertical baffles could increase the illuminance levels by a factor of 2 (Fuller, 1985), compared with diffuse glazing surfaces, see Figure 6-1 and Figure 6-2. For that, ceiling baffles and windows louvres are also proposed to improve the daylighting levels, in the toplighting and sidelighting systems, according to the following:

- Addition of internal louvers/baffles integrated in the roof light and ceiling
- Addition of external louvers in windows

C. Adding internal louvers/baffles (tilt: 40°, 130°)

The addition of internal louvers/baffles in the roof light and ceiling, with vertical louvres (blade dimensions: 0.60m depth; thickness: 0.12m; colour: anodised grey; tilt angle: 40°+ 130°), is proposed in two case studies: CEM EI and CEM VH buildings, see Figure 6-3.

D. Adding external louvers (tilt: 0°)

The addition of external louvers/baffles with horizontal louvres in existing window (blade dimensions: 0.60m depth; thickness: 0.12m; blade colour: anodised grey; tilt angle: (0°), is proposed in the CEM EI building, see Figure 6-3 and Figure 6-4.

6.3.2 Reducing glare sources: filtering and diffusing daylight

The goal of this strategy is to reduce the existing and potential glare sources from sidelighting, especially from windows located on the sides of the playing area, affecting mostly the central area of the users' FOV. To increase the control and diffusion of sunlight, especially from windows in the court and tribunes, the reduction of the glass transmission factors is proposed, to avoid the risk of glare sources in the users' FOV.

E. Decreasing glass transmission factor

The replacement of existing windows with a low glass transmission factor is proposed in the CEM EI, CEM VH and INEFC buildings, see Figure 6-4 and Figure 6-5.

6.3.3 Reducing excessive contrast and improving luminance uniformity

The aim of these measures is to reduce excessive contrast between interior surfaces, improving the luminance uniformity and the overall perception in the users FOV. It is also to improve the overall visual perception of the luminous scene. There are three measures proposed to modify the interior surfaces:

- Increasing the internal reflections from opaque materials by finishing properties of ceilings and side walls: reflectance factor and colour
- Soften hard frames in toplighting systems, by modifying the geometry and splaying edges: between roof lights (translucent) and the ceilings (opaque), see Figure 6-2
- Adding bright surfaces on the ceiling by artificial light

Requirements	Design strategies	Measures	Architectonic elements	Case studies	Variables
Quantity of light					
Minimum E_h illuminance level, and + E_h Uniformity on the court/ playing area	**Increasing daylight admittance** and **illuminance uniformity** by roof light variations	A. Increasing sky dome aperture- θ	monitor roof	CEM VH	AI-0: vertical glazing θ=34° (baseline) AI-1: horizontal glazing (flat skylight) θ=90°
			roof light	CEM EI	AII-0: 5.80m width (baseline) θ=81° AII-1: 7.80m width θ=110°
		B. Increasing glass transmission factor	monitor roof/ roof light	CEM VH INEFC	BI-0: 0.50 (baseline) BI-1: clear 0.85
Quality of light					
Minimizing absolute glare,	**Integrating solar shading devices**: • obstructing, • reflecting, and • re-directing daylight	C. Adding internal louvres/baffles	monitor roof /roof light	CEM EI CEM VH	C-0: no louvres (baseline) C-1: 4u 40° + 4u 130° (tilt)
		D. Adding external louvres	side widows	CEM EI	D-0: no louvres (baseline) D-1: 3u 0° (tilt) D-2: 3u 20° (tilt)
	Reducing glare sources: • filtering, and • diffusing daylight	E. Decreasing glass transmission factor	side widows	CEM EI CEM VH INEFC M	E-0: 0.85 (baseline) E-1: 0.60 E-2: 0.40 E-3: 0.20
adaptation glare, and		F. Increasing reflectance factors + colours	ceiling	CEM VH	FI-0: white 0.90 (baseline) FI-4: yellow 0.85
				PEG	FII-0: black 0.02 (baseline) FII-1: grey 0.50 FII-2: light grey 0.70 FII-3: white 0.90
	Reducing excessive contrast and improving luminance uniformity: • increasing internal reflections, • soften hard frames between glazing and opaque surfaces • increasing brightness of opaque surfaces by artificial light		side walls	CEM VH	FIII-0: orange brick 0.19 (baseline) FIII-1: orange brick 0.40 FIII-2: orange brick 0.60 FIII-3: white brick 0.85
dark and gloomy perception of the luminous environment		G. Adding splayed intersections	roof light/ ceiling	INEFC	GI-0: baseline GI-1: pyramidal shape=
				PEG	GII-0: baseline GII-1: pyramidal shape= GII-2: pyramidal + round
		H. Adding luminaries	ceiling	INEFC	HI-0: no artificial light (baseline) HI-1: squares L=750cd/m^2 HI-2: squares L=500cd/m^2 HI-3: squares L=250cd/m^2
				PEG	HII-0: no artificial light (baseline) HII-1: lines L=250cd/m^2

Table 6-1. Table showing the relation between visual comfort requirements, design strategies, measures and variables proposed for the four case studies of the final sample: CEM EI, CEM VH, INEFC and PEG buildings.

F. Increasing reflectance factors + colours

The increment of reflectance factors and the change of colours on the ceilings is proposed in the CEM VH, and PEG buildings. The increment of the sidewalls reflectance factors is proposed in the CEM VH building.

G. Adding splayed intersections

The shape variations of the existing intersections between roof light and ceiling (glazing/opaque surfaces) by splayed /tilted surfaces, are proposed to minimize the sharp edges and right angles, in the INEFC and PEG buildings.

Increasing the ceiling brightness by artificial light

The addition of bright surfaces of artificial lighting on the ceiling are proposed to compensate the luminance distribution and reducing the contrast between rooflight glazing and opaque surfaces.

H. Adding luminaires

The addition of integrated luminaires on the ceiling are proposed in two forms: squares and in-line. The bright squares are implemented in the INFEC building, and the bright lines are implemented in the PEG building.

6.4 Chapter conclusions

Daylighting design strategies were selected and suggested to improve the visual comfort, taking into account the results of existing sports halls in Catalunya and best practices.

Based on these strategies and available current technologies, specific measures were suggested with the aim to fulfil the visual requirements for athletes, spectators and remote spectators.

Measures with different levels of intervention resulted to be implemented in four Olympic sports halls or final sample, to modify the luminous environment by architectonic elements such as ceiling, side walls, windows and roof lights, solar control devices and glazing surfaces.

These measures included modifications of the main architectonic surfaces such as reflectance factors, colours and glazing transmission factors of toplighting and sidelighting systems. Likewise, elements for solar protection, daylight control and artificial lighting were also incorporated.

The majority of measures suggested were passive, since they do not require mechanical and electrical devices to function, with the exception of the addition of artificial lighting on the ceiling surface.

The majority of measures involved also a low level of intervention in retrofitting practices, especially considering its application in in-use buildings. By contrast, those proposed to increase the natural lighting level on the court, may be considered as major interventions. Alterations in the geometry and shape of the roof lights are examples of that.

Finally, it is considered that the suggested daylighting design strategies and measures should be simulated and tested by users, with the aim to assess their effectiveness for visual comfort in daylit sports halls. In addition, the subjective perception of users and their preferences could be also useful to be explored, considering different daylit environments to play and watch sports activities.

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7

Experimental test and discussion of results

Daylight design strategies and measures for toplighting and sidelighting were suggested in Chapter 6 to be integrated in four Olympic buildings of the final sample. Experimental tests by panel were carried out at the Habitat Sciences Laboratory -LASH, Département Génie Civil et Bâtiment – DGCB, Ecole National de Travaux Publics de l'Etat- ENTPE, under the direction of Prof. Marc Fontoynont. The international research stay was supported by "Scholarship for research stays outside Catalonia, BE 2010", during three and half (3.5) months, see Appendix IV, section A, pp. 2-53.

This chapter presents and discusses the quality and quantity analysis of the open-ended and closed-ended panel responses, completed after the test realization. Quality information obtained from panel responses, such likes and dislikes, are linked with objective data obtained to explore the users' preferences in sports halls.

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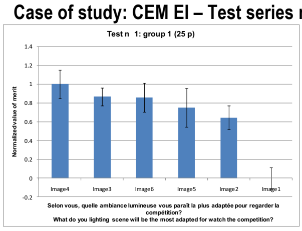
7.1 Experimental psycho-visual test

The experimental test was designed to evaluate the effectiveness of the measures by panel, to objectively qualify and quantify the visual comfort in sports halls. For that, daylight strategies and measures for toplighting and sidelighting systems, suggested in the previous chapter, were integrated by static simulation. Photorealistic HDR images were obtained to allow the subjects to compare the existing conditions and scenarios with improvements of four Olympic buildings, with the focus in the visual comfort. Also, 256no. questionnaires with participants' responses were obtained at LASH-ENTPE, see Appendix IV, section A, pp. 2-53.

Test results: Athlete	**Most preferred image**	**Less preferred image**

Case of study: CEM EI – Test series nº 1. Athlete point of view, group 1 (25 subjects)

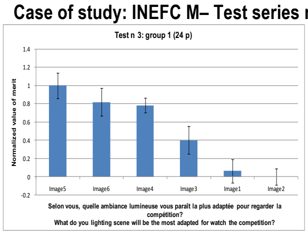


CEM EI - Value of merit

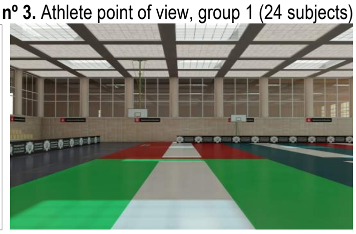
CEM EI- Image 4- Improvement measures in lateral windows: transmission glass coefficient 20%.

CEM EI- Image 1- Reference image, real situation. Lateral windows, transmission glass coefficient 85%.

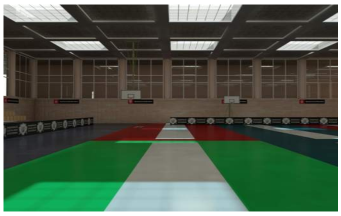
Case of study: INEFC M– Test series nº 3. Athlete point of view, group 1 (24 subjects)



INEFC - Value of merit

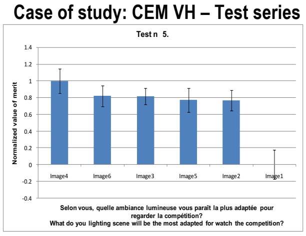


INEFC- Image 5 - Improvement measures in top lit system: addition of artificial lighting in opaque ceiling surface: 500 luminance level.



INEFC- Image 2 Improvement measures in lateral windows, transmission glass coefficient 20%.

Case of study: CEM VH – Test series nº 5. Athlete point of view (32 subjects)

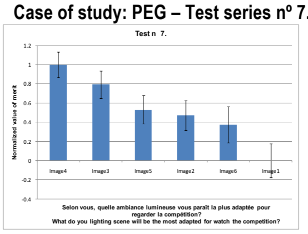


CEM VH- - Value of merit

CEM VH- Image 4 - Improvement measures in top lit system: increasing and change orientation of glazing area (0º horizontal, skylight), glazing transmission factor 85%, solar shading device (zenith: 4 Nord and 4 South, orientation 40°). Improvement measures in lateral windows: transmission glass coefficient 60%.

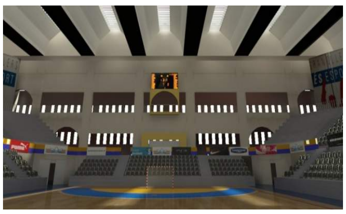
CEM VH- Image 1- Reference image, real situation. Lateral windows: transmission glass coefficient 85%; interior walls reflection coefficient 19% (orange brick) and solar shading device. Top lit system: orientation of glazing area 90º Nord (Saw-tooth system), glazing transmission factor 50%, and ceiling colour: white.

Case of study: PEG – Test series nº 7. Athlete point of view (32 subjects)



PEG - Value of merit

PEG- Image 4 - Improvement measures: in ceiling colour white and transmission coefficient 90%.

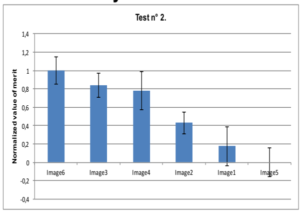


PEG- Image 1- Reference image, real situation. Lateral windows: transmission glass coefficient 85%; interior walls reflection coefficient 70% (white) and concrete walls 20%. Top lit system: skylight, glazing transmission factor 65%, interior of skylight white (85%) and ceiling colour: black (transmission coefficient 2%)

Figure 7-1. Results of the visual test obtained for athtlete view point: value of merit, left, most preferred image, center, and less preferred image, right.

Test results: Spectator and TV broadcasting	Most preferred image	Less preferred image

Case of study: CEM EI – Test series nº 2. Spectator and TV broadcasting, group (32 subjects)

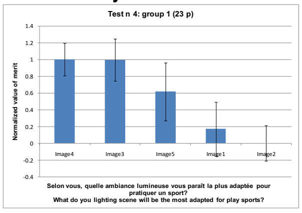


CEM EI- Value of merit

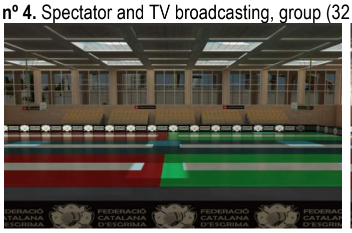
CEM EI- Image 6 - Improvement measures in top lit system: solar shading device (zenith: 4 Nord and 4 South, orientation 40°), increasing glazing area (7,80 width), glass transmission coefficient: 85%. Improvement measures in lateral windows: solar shading device Nord and South (3 blades, orientation 0°)

CEM EI- Image 5 - Improvement measures in top lit system: solar shading device (zenith: 4 Nord and 4 South, orientation 40°), glass transmission coefficient: 85%. Improvement measures in lateral windows: solar shading device Nord and South (3 blades, orientation 0°)

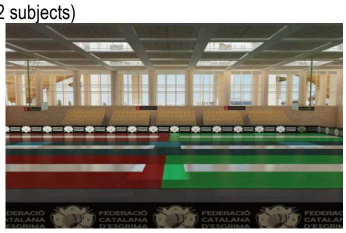
Case of study: INEFC M– Test series nº 4. Spectator and TV broadcasting, group (32 subjects)



INEFC - Value of merit

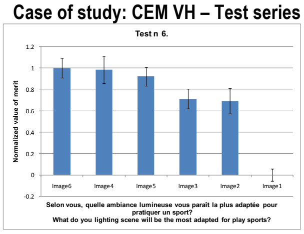


INEFC- Image 4 - Improvement measures in lateral windows, transmission glass coefficient 40%



INEFC- Image 2 - Improvement measures in lateral windows, change of panoramic view (without near exterior elements)

Case of study: CEM VH – Test series nº 6. Spectator and TV broadcasting, group (32 subjects)

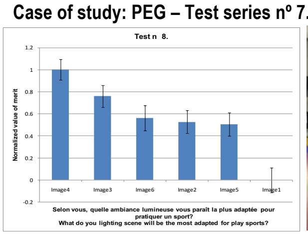


CEM VH - Value of merit

CEM VH- Image 6 - Improvement measures in top lit system: increasing and change orientation of glazing area (0° horizontal, skylight), glazing transmission factor 85%, solar shading device (zenith: 4 Nord and 4 South, orientation 40°), colour of ceiling (yellow). Improvement measures in lateral windows: transmission glass coefficient 20%; interior walls reflection coefficient 85% and colour (white brick)

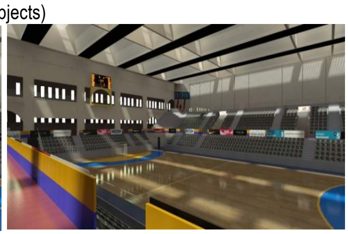
CEM VH- Image 1- Reference image, real situation. Lateral windows: transmission glass coefficient 85%; interior walls reflection coefficient 19% (orange brick) and solar shading device. Top lit system: orientation of glazing area 90º Nord (Saw-tooth system), glazing transmission factor 50%, and ceiling colour: white.

Case of study: PEG – Test series nº 7. Spectator and TV broadcasting, group (32 subjects)



PEG - Value of merit

PEG- Image 4 - Improvement measures: in ceiling colour white and transmission coefficient 90%.



PEG- Image 1- Reference image, real situation. Lateral windows: transmission glass coefficient 85%; interior walls reflection coefficient 70% (white) and concrete walls 20%. Top lit system: skylight, glazing transmission factor 65%, interior of skylight white (85%) and ceiling colour: black (transmission coefficient 2%)

Figure 7-2. Results of the visual test obtained for athtlete view point: Value of merit, left, most preferred image, center, and less preferred image, right.

The overall response for the improvement measures implemented was very positive.

The test results show that the measures for the improvement of visual comfort were preferred by the majority of the participants.

A-posteriori, a quality assessment of the open-ended responses collected from the panel was completed to extract quality information about the justification criteria for the most and less preferred images or luminous scenes obtained by simulation. These results are presented and discussed in this chapter, according to the procedures described previously in Chapter 3.

Judgement by panel

The panel was composed by 32no. subjects or participants who performed the tests, according to the next demographic information, that shows gender, age group, occupation, if participants wear corrective glasses or contact lenses, vision issues, and if they have previous experience in visual tests, see Figure 7-3.

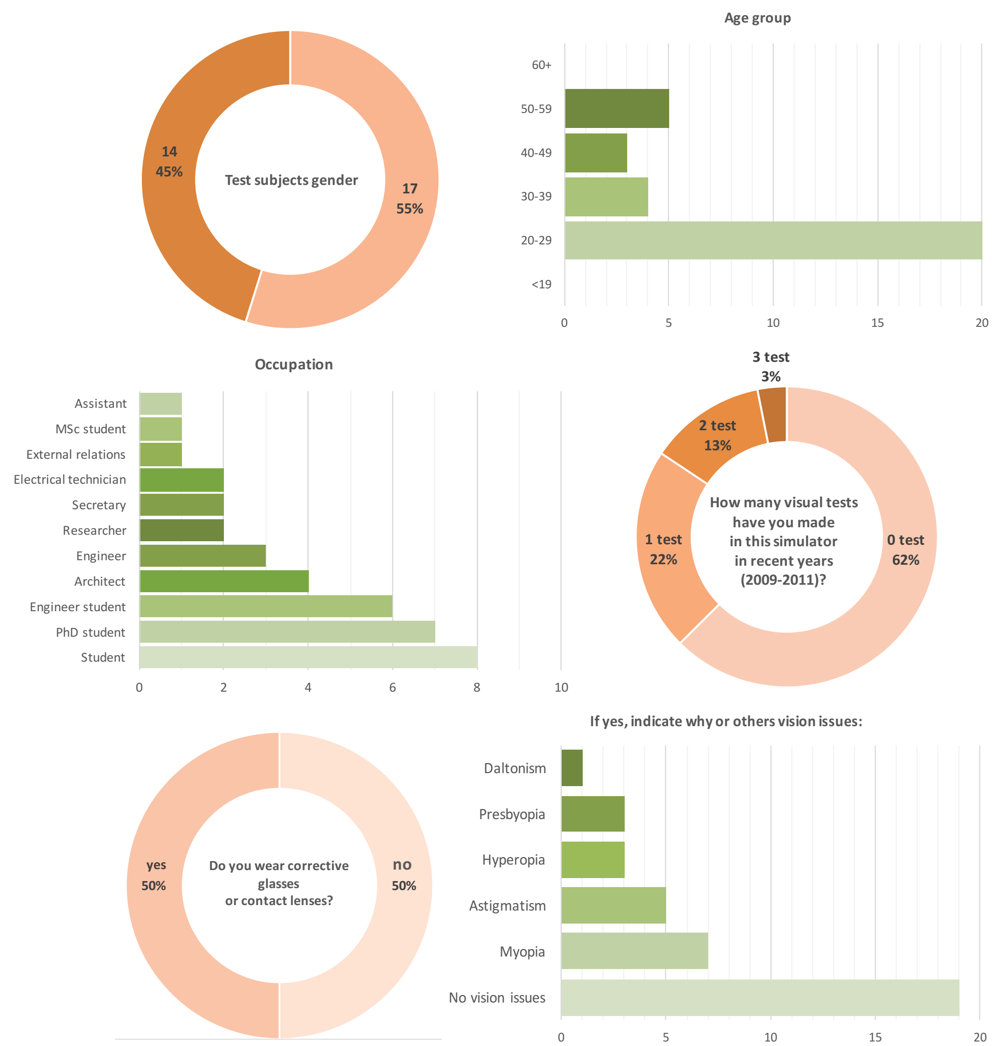
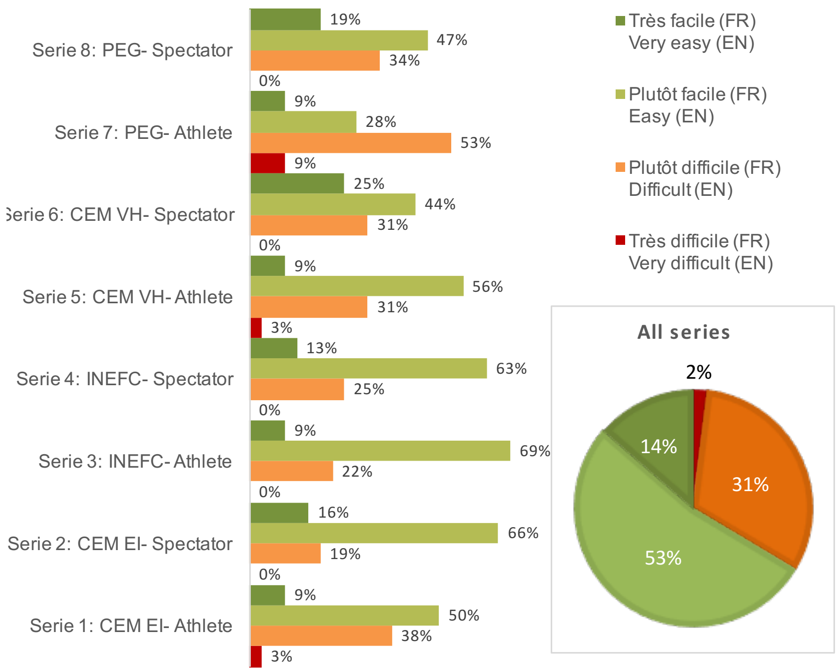


Figure 7-3. Graphics showing the demographics of the panel: original language (FR) and translation by the author (EN).

Doughnut and bar charts showing: a) the gender and the age group, b) the occupation and if subjects had participated in visual test in the lab in recent years, c) if the participants wear corrective glasses or contact lenses and type of vision issues.

Selon moi, ce test était : (FR)   This test was : (EN)



Pour effectuer le test, étiez-vous dans une situation confortable? (FR)

Were you comfortable during the test? (EN)

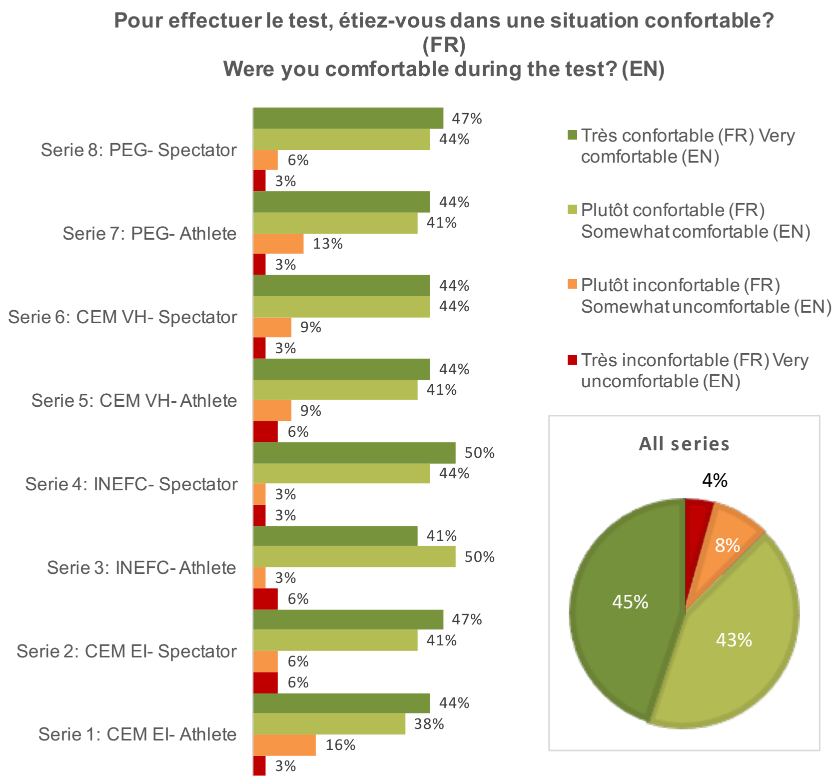


Figure 7-4. Graphics showing the level of difficulty and comfort experienced by panel during the test: bar chart of each series, and pie chart with all series: original language (FR) and translation by the author (EN).

a) level of difficulty: 14% very easy, 53% easy, 31% difficult, and 2% very difficult

b) level of comfort experienced: 45% very comfortable, 43% somewhat comfortable, 8% somewhat uncomfortable and 4% very uncomfortable

7.2 Series questionnaire results

Level of difficulty of test

Considering the overview of level of difficulty of the test realization of all series, two-thirds of the panel expressed that it was easy: “very easy” with 14% and “easy” with 53%. However, one-third expressed that was “difficult” with 31% and “very difficult” with 2%.

In order to find the reasons to justify the previous question responses, the word frequency analysis shows that “differences” and “different” are among of the most used words, followed by “easy”, “clear”/ “defined”. These results suggest a positive correlation with the previous question, where almost of two-thirds expressed that the experience was easy and very easy. In the same way, the proportion of words “difficult”, “similar”, “same” are in accordance with one third that expressed the test was difficult and very difficult, particularly in test N° 1 CEM EI Athlete and N° 7 PEG Athlete, as shown in bar charts of each series, see Figure 7-4.

Level of comfort during the test

The next question of the test experience is about the level of comfort/ discomfort during the test. The majority of subjects were comfortable during the test, with 45% of “very comfortable”, followed by “somewhat comfortable” with 43%. A minority of respondents expressed that they felt “somewhat uncomfortable” with 8% and “very uncomfortable” with the 4%. In the majority of responses from the Athletes test series, subjects expressed higher percentages of “very uncomfortable” (6%) and “somewhat uncomfortable” (16%), as shown in the bar charts of each series, see Figure 7-4.

7.2.1 Luminance maps analysis

In order to correlate the subjective data obtained by subjects’ responses with objective data from luminance maps, the most and less preferred images were analysed with DESKTOP RADIANCE software (LBNL 2000, version 2.0 Beta 2.1) and PHOTOSPHERE software (Ward 2014, version 1.8.16U), see *Figure 7-18* and Figure 7-19.

7.2.2 Quantity and quality assessment of the subjects’ responses

The results of the series questionnaires n° 2 are presented below by extracting most frequent words and lexical items from a word-based analysis approach.

Frequency analysis: most used words in text

The results show similar lexical density in most and less preferred images, which gives a text the meaning, in terms of nouns, adjectives, verbs and adverbs.

The most frequent words used by participants were extracted in three groups: about the level of difficulty/easiest of the test realization, and to justify the choices for the most and less preferred images. The basic analytics are presented in the following, see Table 7-1.

Analysis of open-ended responses	Images selection	Most preferred images	Less preferred images (rejection)
Number of characters (including spaces):	14344	16384	13718
Number of characters (without spaces):	11535	13207	10966
Number of words:	2282	2505	2505
Lexical Density:	225.241	185.230	176.046
Number of sentences:	83	270	302
Number of syllables:	3808	4268	3486

Table 7-1. Results of the analysis of the text from the open-ended responses by Online-Utility.org software (Adamovic 2009, version 2) Source: www.oline-utility.org/text/analyzer.jsp

a) image selection, in grey colour, b) most preferred images, in green colour, c) less preferred or rejection, in orange colour

Level of difficulty of the test

The most used words to choose the images are: images, differences, different, choice, easy, clear, difficult, enough, good, comparison/s, see Figure 7-5.

Frequent words

	FR	EN (translation)
1	images	images
2	différence/s	difference/s
3	différents, differentes	different
4	choix	choice, decision
5	facile	easy
6	nettes	clear, defined
7	difficile	difficult
8	assez	enough, sufficient
9	bien	good
10	comparaison/s	comparison/s
11	comparer	to compare
12	luminosité	light, luminosity, brightness
13	différence/s	difference/s
14	était	was
15	lumière	light, lights, lighting, daylight
16	contraste	contrast
17	similaires	similar
18	vue	sight, view
19	photos	photos
20	éclairage	lighting, lights, light, light/ lighting level
21	entres	go inside
22	facilement	easily
23	même	same
24	spectateur	spectator
25	terrain	court, field of play

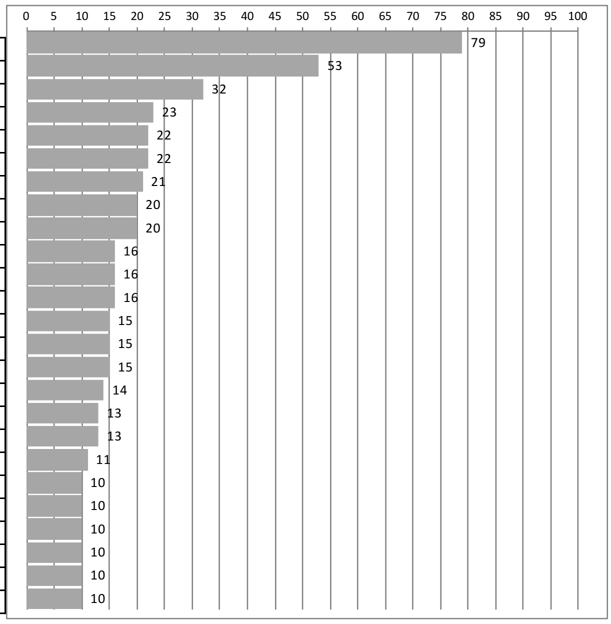


Figure 7-5. Bar chart showing the word frequency analysis about the level of difficulty/easiest of test realization by participants: the first 25 most used words original language (FR) and translation by the author (EN).

Most preferred images

The most used words for the most preferred images are: court, light, luminosity, brightness, sunlight, daylight, lighting level, good, ceiling, luminous, reflects, see Figure 7-7.

The most used words for most and less preferred images are represented in word clouds. Note that the biggest size of the word represents the most frequent word used in word clouds, see Figure 7-6 and Figure 7-*8*

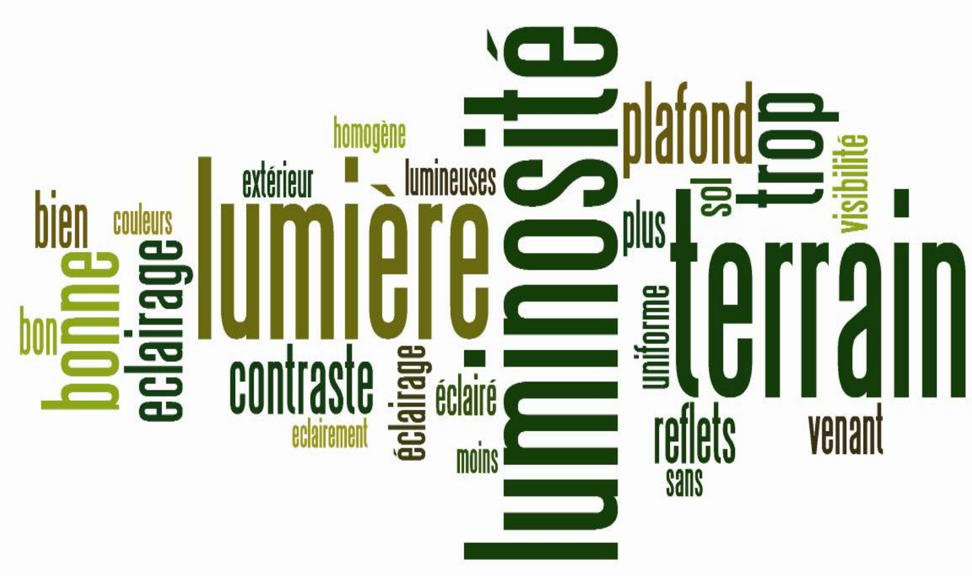


Figure 7-6. Word cloud showing the word frequency analysis about the most preferred images: the first 25 most used words by participants (French language).

Frequent words

	FR	EN (translation)
1	terrain	picht, court, field of play
2	luminosité	light, luminosity, brightness
3	lumière	light, sunlight, daylight,
4	éclairage	lighting, lights
5	bonne	good, right
6	plafond	ceiling
7	lumineuse, lumineux, lumineuses	bright, light, luminous
8	contraste	contrast
9	reflets	reflects
10	bien	good
11	venant	coming from
12	bon	good, right
13	sol	floor
14	éclairement	illumination, light, brightness
15	visibilité	visibility
16	uniforme	uniform
17	éclairé	lit, lighted, lit up
18	extérieur	outside, outdoor, outdoors
19	couleurs	colours
20	homogène	homogeneous
21	éblouissement	glare, dazzling
22	fenêtres	windows
23	vue	sight, view
24	ambiance	ambience, ambient, atmosphere
25	couleur	colour

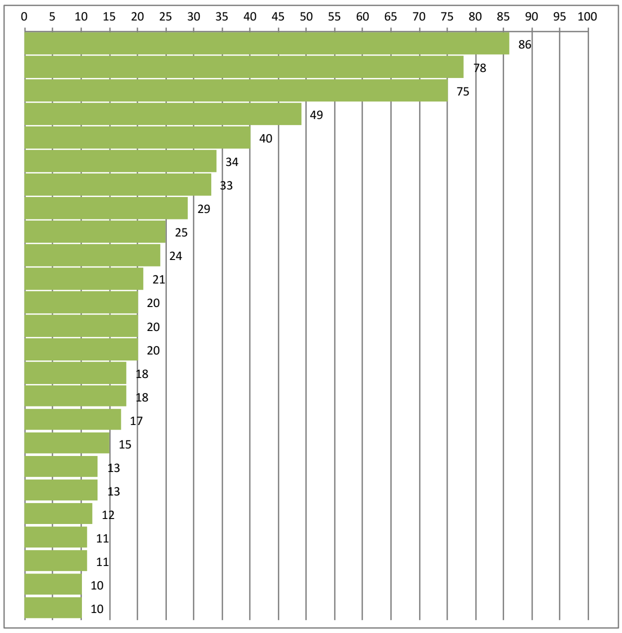


Figure 7-7. Bar chart showing the word frequency analysis about the most preferred images: the first 25 most used words: original language (FR) and translation by the author (EN).

Less preferred images

The most used words for the less preferred images are: shadow/s, light, lighting, daylighting, lighting level, court, reflects, reflections, glare, contrast/s, luminosity, floor, ceiling, bright, see *Figure 7-9.*

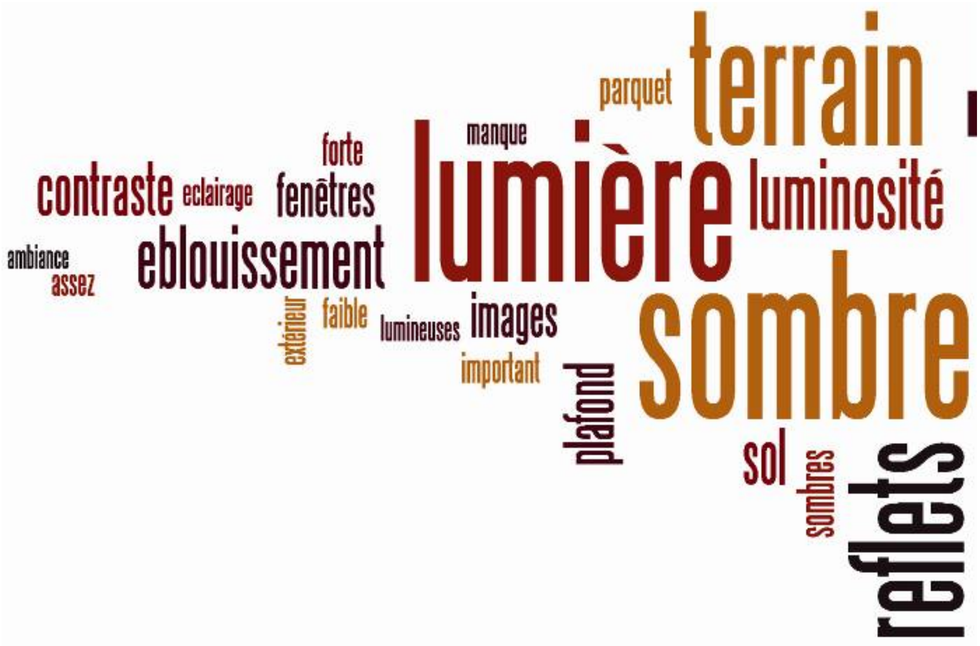


Figure 7-8. *Word cloud showing the frequency word analysis about the less preferred or rejected images: the first 25 most used words by participants (French language).*

Frequent words

	FR	EN (translation)
1	sombre, sombres	sombre, dark, gloomy
2	lumière	light, lights, lighting, daylight
3	terrain	picht, court, field of play
4	reflet, reflets	reflection
5	éblouissement	glare, dazzling
6	contraste, contrastes	contrast, contrasts
7	luminosité	light, luminosity, brightness
8	sol	floor
9	plafond	ceiling
10	lumineuses, lumineux	bright, light, luminous
11	éclairage	lighting, lights, light / lighting level
12	fort, forte	strong, large
13	important, importante	important, essential
14	fenêtres	windows
15	images	images
16	parquet	parquet, wood floor
17	zone, zones	zone/s, area/s
18	éblouissant, éblouissante	glaring, dazzling
19	faible	weak, light, low
20	assez	enough, sufficient
21	manque	lack, shortage, absence
22	extérieur	outside, outdoor, outdoors
23	ambiance	ambience, ambient, atmosphere
24	fond	back, background
25	vive	strong, bright
25	venant	coming from

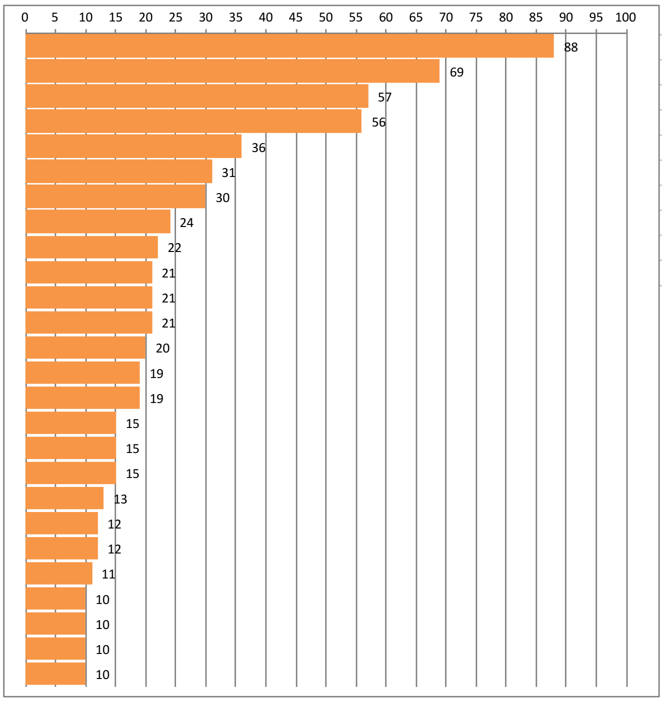


Figure 7-9. *Bar chart showing the word frequency analysis about the less preferred or rejected images: the first 25 most used words: original language (FR) and translation by the author (EN).*

Key words in context

Once the frequency word analysis was completed, a text analysis was processed to extract key themes and categories from the statements made by subjects (key words in context KWIC or co-occurrences of words).

Following, the main ideas were extracted and classified in different themes and subgroups. Finally, the results were clustered in six main categories as follows:

- Quality of light
- Quantity of light
- Architectural features
- Type of light: daylight and artificial
- Exterior views
- Other

Frequent words

	FR	EN
1	lumière	light, lights, lighting, daylight
	luminosité	light, luminosity, brightness
	lumineuse, lumineux, lumineuses	bright, light, luminous
2	terrain	picht, court, field of play
	sol	floor
	parquet	parquet, wood floor
3	éclairage	lighting, lights, light, light/ lighting level
	éclairé	lit, lighted, lit up, illuminated
	éclairement	illumination, light, brightness
4	images	images
	photos	photos
5	ombre/s	shade, shadow
	sombre, sombres	sombre, dark, gloomy
	obscurité	dark, darkness
6	bien	good
	bon, bonne	good, right
7	reflet, reflets	reflection
8	différence/s	difference/s
	différents, differentes	different
9	éblouissement	glare, dazzling
	éblouissant, éblouissante	glaring, dazzling
10	contraste, contrastes	contrast, contrasts
11	plafond	ceiling
12	couleur/s	colour
13	assez	enough, sufficient
14	uniforme	uniform
	homogène	homogeneous
15	fenêtres	windows
	ouvertures	openings
16	important/s, importante	important, essential
17	facile	easy
	facilement	easily
18	venant	coming from
19	vue	sight, view
20	fort, forte	strong, large
21	extérieur	outside, outdoor, outdoors
22	choix	choice, decision
23	suffisant/e	enough, adequate, sufficient
24	nettes	clear, defined
25	difficile	difficult
26	ambiance	ambience, ambient, atmosphere
27	faible	weak, light, low
28	visibilité	visibility
29	gradins	grandstand, terraces, bleachers
30	salle	hall

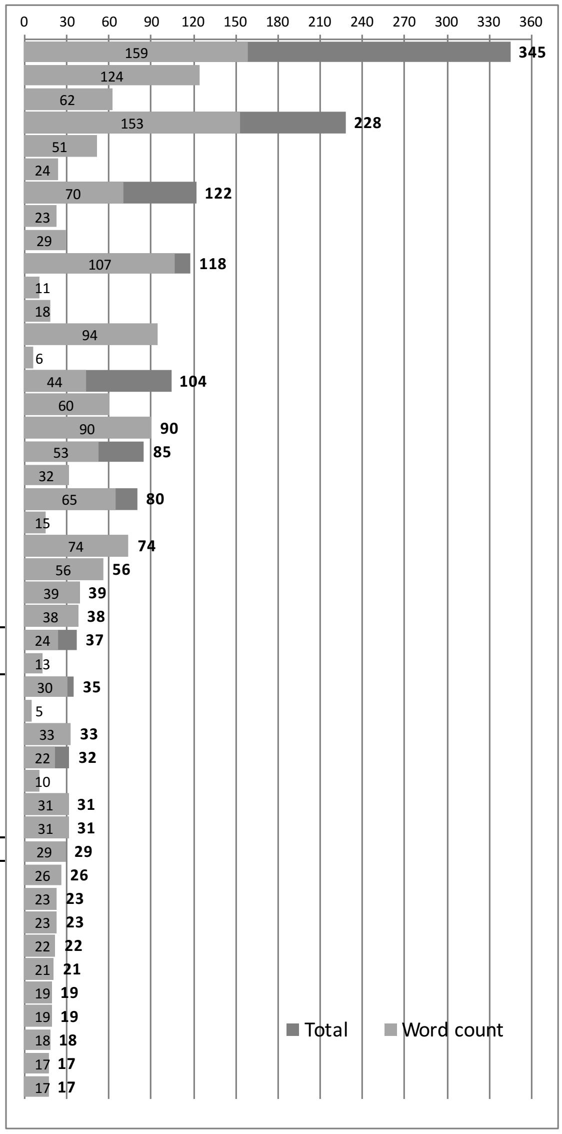


Figure 7-10. Bar chart showing the word frequency analysis about the total of the open-ended survey responses, including justification for the most and less preferred images: the first 30 most used words: original language (FR) and translation by the author (EN).

Quantity of light

In the group of quantity of light, key words or succession of words related to the light in general were identified, the way light is perceived and the amount of light described: light/ lighting/brightness/level of light, different lighting levels, strong light, good/enough/sufficient light, indirect/filtered/diffuse/dimmed light and minimum level of light, no darkness/shadows/gloom, etc., see Table 7-2.

Items	(FR) original source	(EN) translation
1	Quantity of light category	
L	Luminosité, lumière, éclairage	Light, luminosity, brightness, lights, daylight, lighting, lighting level
No SH	Pas d'ombre, sombre, obscurité, noir	No sombre, shade, shadow, dark, darkness, gloom, black
SH	Trop d'ombre, sombre, obscurité, manque de lumière	Too much sombre, shade, shadow, dark, darkness, gloom, lack of light
L min	Lumière/ éclairage: peu, minimum, trop faible	Level of light: low, minimum, too low/weak/poor
L dif	Lumière/ éclairage: tamisé, diffuse, atténué, douce	Light filtered, diffuse, dimmer, soft, gentle
L ave1	Lumière, lumineuses éclairage: mais pas trop	Level of light: average, bright but not too much
L ave2	Lumière, éclairage: assez, suffisant, bien, bonne	Level of light: good, adequate, enough
No L ave2	Lumière, éclairage: pas assez, pas suffisant	Level of light: not good, not adequate, not enough
L Max	Lumière, éclairage: plus, forte, importante	Level of light: maximum, large, significant amount
L dir	Lumière, éclairage: trop directe, vive, agressive	Level of light: too direct, strong/bright, aggressive

Table 7-2. Table showing the most referred items identified or lexical words, from the open-ended responses: quantity of light category and sub-categories, original language (FR) and translation by the author (EN).

Quality of light

In the group of the quality of light, the terms identified are related with parameters or attributes of the light. The most frequent are: homogeneity/uniformity, glare/dazzling, reflects/reflections, colours (including cold- blue and warm-yellow), visibility, contrast, focalization/accent, see Table 7-3.

Items	(FR) original source	(EN) translation
2	Quality of light category	
U-H No U-H	Uniforme, homogène No uniforme, homogène	Uniform, homogeneous No uniform, homogeneus
CL	Couleur	Colour
CL-W	Couleur chaude, jaune	Warm colour, yellow
CL-C	Couleur froide, bleu	Cold colour, blue
G	Non, pas éblouissant	No glare, dazzled
V Low V	Visibilité, rendu, visible	Visibility, rendering, visible Low visibility, rendering, visible
R	Non reflets, réflexions, tâches lumineuses, bandes lumineuses, lumières parasites	No reflects, reflections, light/sun spots
CN High CN No CN	Contraste, contrastée, carres de lumière Trop de contraste Pas de contraste	Contrast, contrasted High contrast No contrast, low
F No F	Focalisation, plus lumineux que le reste (tribune, gradins, spectateurs) No focalisation (tribunes éclairées = comme le terrain)	Focus, accent, brighter than the rest (grandstand, stand, spectators, terraces= seating area) No focus, (grandstands lighted = terrain)

Table 7-3. Table showing the most referred items identified or lexical words, from the opened-ended responses: quality of light category and sub-categories, original language (FR) and translation by the author (EN).

Architectural features

About the architectural features category group, different elements were extracted and clustered from most referenced items from the text, such as: "court/field of play/pitch/playing zone", ceiling, ambiance, floor, walls/background/back walls, windows, glass, sides, grandstands, basket/goal, field of view - FOV, lines on the floor, blades, etc., see Table 7-4.

Items	(FR) original source	(EN) translation
3	Architectural features category	
Court	Terrain, zone de jeu, le piste, zone de match	Court, field of play, pitch, playing zone
Floor	Sol, parquet	Floor, parquet, wood floor
Ceiling	Plafond, toit, toiture	Ceiling, roof
Windows	Fenêtres	Windows
Glass	Les vitres	Glass/ess, glazing area
Ambiance	Ambiance, gym, gymnase, salle, images, scène, scenario	Ambience, gym, sport hall, hall, images, scene, situation
Basket, goal	Panier, but, panneau*, gol	Basket, goal,
Lines on the floor	Marquages au sol,	Lines on the floor
Sides	Latérale, côtes,	Laterals, sides
Grandstand	Tribunes, gradins, spectateurs,	Grandstand, terrace, bleachers, spectators' seating area
Walls	Mur, fond, mur du fond	Walls, back, background, back walls
Blades	Ailettes, barres,	Blades, louvres
FOV	Le sportif, en face, on est en face, venant d'en face	Field of view
No specified/ light	Uniformité, lumière éblouissante, FR	References to general concepts, or items that cannot be co-related with others items in the previous categories, or referring to the characteristics of lighting or light, e.g.: uniformity, glaring light, EN

Table 7-4. Table showing the most referred items or lexical words identified in open-ended responses: architectonic features category and sub-categories, original language (FR) and translation by the author (EN).

Type of light, external views and others

The last three categories are: the "type of light", "exterior views" and "other", see

Table 7-5.

The "type of light" category includes: "artificial", "daylight/sunlight/outdoors" and "no daylight" (low transmission glazing area).

The "exterior views" category includes the possibility to have outdoors views, most of all by windows, and the contrary, "no exterior views" (No EV).

In the "other" group, the responses that could not be assigned to any of the previous categories obtained are listed. For example, the sentences suggesting to be related to some key words, but imprecise in terms to be linked to the main categories, or if certainly is a cause to select or to reject the image:

- *"Présence d'ailettes sur les côtés est importante"*, FR. Presence of blades in the sides are significant, EN.
- *De nuit l'éclairage intérieur est un peu fort", FR.* At night, the interior lighting is a bit strong, EN.

In the first example, the <sides> and <blades> are architectonic features identified but the meaning of <are significant> is unclear in terms of selection or elimination, like or dislike.

The last two sentences are imprecise again, in terms of image selection or rejection. However, the most significant evidence extracted from this example is that the low transmission glazing windows were perceived by one third of subjects as the scene happened at night time, or with "low exterior lighting level" or "dark exterior reflections".

Moreover, a small number of participants suggested they felt a sensation of isolation and insecurity, sadness and being enclosed. Additionally, it was not perceived in the same way by the total of subjects during the test, because some of them stated that they prefer the high transmission or low glazing windows and the outdoors view.

Furthermore, note that there were some arguments that subjects used for both decisions: most preferred and less preferred, but in negative or positive sentences. For example, to justify the preference the sentence was:

- *"Terrain bien éclairé et uniformément"*, FR. Well-lit and uniform court or playing area, EN.

For the rejection of the image the sentences was:

- "*Eclairage trop sombre. Trop de zone d'ombre au sol"*, FR. Poor or low lighting levels, too much shadows on the ground or playing area

In fact, the idea or reason exposed by participants is the same in terms of quantity of light on the playing area, but was expressed in positive and negative sentences.

Items	(FR) original source	(EN) translation
4	Type of light category	
DL	Luminosité, lumière, éclairage: naturelle, soleil, extérieur	Daylight, natural light, sunlight, exterior
AL	Luminosité, lumière, éclairage: artificiel	Artificial light
No DL	L'obscurité extérieure, stores fermés, fenêtres noires, pas de lumière du jour	No daylight: exterior darkness, shut-down stores, black windows, no daylight
5	Exterior views category	
EV	Vue sur l'extérieur, le ciel, le bâtiments	Exterior view/sight. View of outdoors, sky, buildings
No EV	Pas de vue sur l'extérieur, le ciel, le bâtiments	No exterior view/sight of: outdoors, sky, buildings
6	Others category	
Others		Items that cannot be assigned in any of the previous categories.

Table 7-5. Table showing the most referred items or lexical words identified in open-ended responses: type of light, exterior views, and others categories and sub-categories: original language (FR) and translation by the author (EN).

7.2.3 Most preferred images

The results from the most preferred images responses with 556 units extracted from 270 sentences. The main categories are: quantity of light 46%, quality of light 45%, type of light 4% and exterior views and others with 2% (total of 270 sentences), see Figure 7-11.

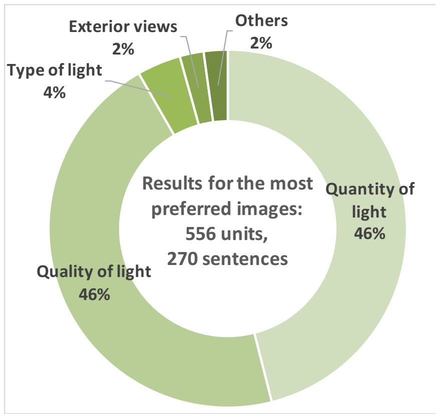


Figure 7-11. Doughnut chart showing the text analysis of the most preferred images responses and percentages of the five categories extracted.

Quantity of light

The most frequent themes extracted about the level of light, quantity category are: "good/adequate" 28% and the "level of light", in general, with 27%.

The two most referred categories were followed by "low/minimum" and "maximum/large" with 13%, "average/bright but not too much" and "light filtered/diffuse" 9%, "no sombre/shade" 2%, see Figure 7-12.

Quality of light

The most numerous items extracted in the quality of light are: the "uniform/homogeneous" 21%, "colour" 16%, "no glare/dazzled" 16%, "visibility" 14% and "no-reflects/reflections" 13%, followed by "contrast" 9% and "focus/accent" in the court 6%, see Figure 7-12.

The most referred categories for user preferences in quantity and quality of light were the architectonic elements with 52% and the "no specified" with 30%.

The two last categories are "Light/ lighting" with 17% and "field of view - FOV" with 1%, see Table 7-6.

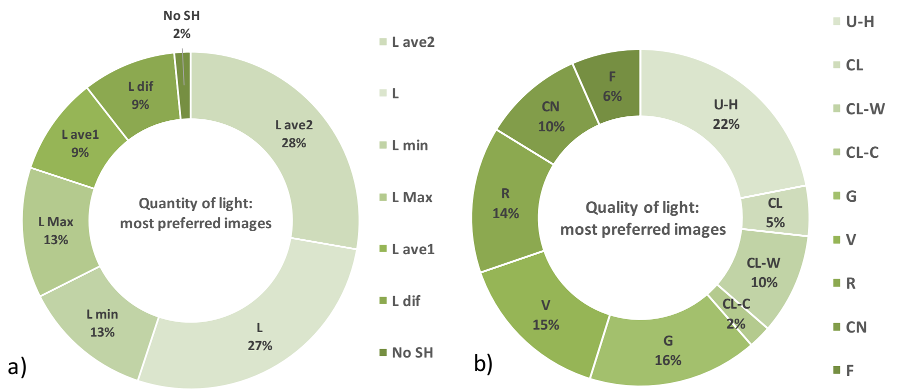


Figure 7-12. Doughnut charts showing the text analysis about the most preferred images responses. most referred items (%) in quantity of light and b) quality of light categories

Architectonic features

The most numerous architectonic features stated are: the "court" with the 38% (50 and 63 times in quantity and quality of light respectively) and "ceiling" with 18%, followed by windows 9%, "ambiance" and "floor" with 8%.

The last sub-categories are the "grandstands", "basket/goal" and "sides" with 5%, "lines on the floor" with 3% and "walls/background" with 1%, see Table 7-6 and Figure 7-13.

Type of light, exterior views and others

The most referred themes were the "type of light" with the 4% showing the most numerous entries for the preference for "natural light", followed by the "exterior views" and "other" with 2%.

The ideas grouped in "other" are the following examples:

- "*Impression d'ouverture au plafond*", FR. Opening impression/perception at the ceiling, EN.
- "*La manière dont la lumière naturelle pénétrait à l'intérieur (directe ou non, intense ou non)*", FR. The way the natural light penetrates indoors (direct or not, intense or not), EN.

From these examples, the items "ceiling" is identified as architectonic element and "natural light" and "direct or not/ intense or not" are associated as type of light, but results unclear in the context of images' selection or the contrary, images' elimination. Interestingly, both sentences give rich details about subjects' perception and clues related to toplighting (opening impression or perception) and about how natural light day-lit the space (direct and intense light or not).

Most referred categories	Nº of times in Quantity of light	Nº of times in Quality of light	Totals	Percentage %
Architectonic elements	162	137	299	52%
No specified	114	61	175	30%
Light, lighting level	70	27	97	17%
FOV- Field of view		3	3	1%
	346	**228**	**574**	**100%**

Reference to architectonic elements	Nº of times in Quantity of light	Nº of times in Quality of light	Totals	Percentage %
Court	50	63	113	38%
Ceiling	36	18	54	18%
Windows	22	6	28	9%
Ambiance	16	7	23	8%
Floor	4	19	23	8%
Grandstands	15	1	16	5%
Basket/ Goal	5	10	15	5%
Sides	11	3	14	5%
Lines on the floor	2	8	10	3%
Walls, backroung, back walls	1	2	3	1%
	162	**137**	**299**	**100%**

Table 7-6. Tables showing the most referred items in the quantity and quality of light categories about the most preferred images responses.

a) most referred items in quantity and quality of light: architectonic elements, no specified and field of view

b) most referred sub-categories by architectonics elements below: court, ceiling and windows

Most linked items

The most linked items in the subject's preferences in the main categories are the following, see Table 7-7:

– a "good", "uniform/homogeneous" and "focus/ accent" lighting and good "visibility" on the court

– "no reflects, reflections" on the "floor" and in the court, and a good "visibility" of the "lines on the floor"

– a "low, minimum", "no glare" and "filtered/diffuse" light from "windows" with "exterior views"

– "warm/yellow" colour, "maximum" and "low/ minimum" lighting and in the "ceiling"

– a "low, minimum" lighting level in the "grandstands" and "sides"

Quantity of light	L	L ave2	Lmax	Lmin	L ave1	L ave	Totals
Walls, backroung, back walls	1						1
Lines on the floor	1		1				2
Floor			2		2		4
Baskel/ Goal	1	2	1				4
Sides	5			4		2	11
Grandstand	1	1		13			15
Ambiance	7	2			5	1	15
Windows	2			10		3	15
Ceiling	16		5	4		3	28
Court	19	20	5		4		48
No specified	17	19	18	1	16	15	86
Total	**70**	**44**	**32**	**32**	**27**	**24**	**229**

Quality of light	U-H	G	V	R	CN	CL-W	Totals
Floor	3		3	12	1		19
Ceiling	3	2			2	7	14
Windows		5		1			6
Baskel/ Goal			5	1	4		10
Lines on the floor			8				8
Ambiance	1	2				4	7
Sides	2						2
Field of view		3					3
Walls, backroung, back walls						1	1
Grandstands			1				1
Light, lighting level	17	10					27
Court	19	2	11	10	6		48
No specified	5	13	6	8	9	10	51
Total	**44**	**35**	**31**	**20**	**19**	**15**	**164**

Table 7-7. Tables showing the most linked items in the main categories: architectonic elements referred in the quantity (top) and quality of light (bottom) categories about the most preferred images responses.

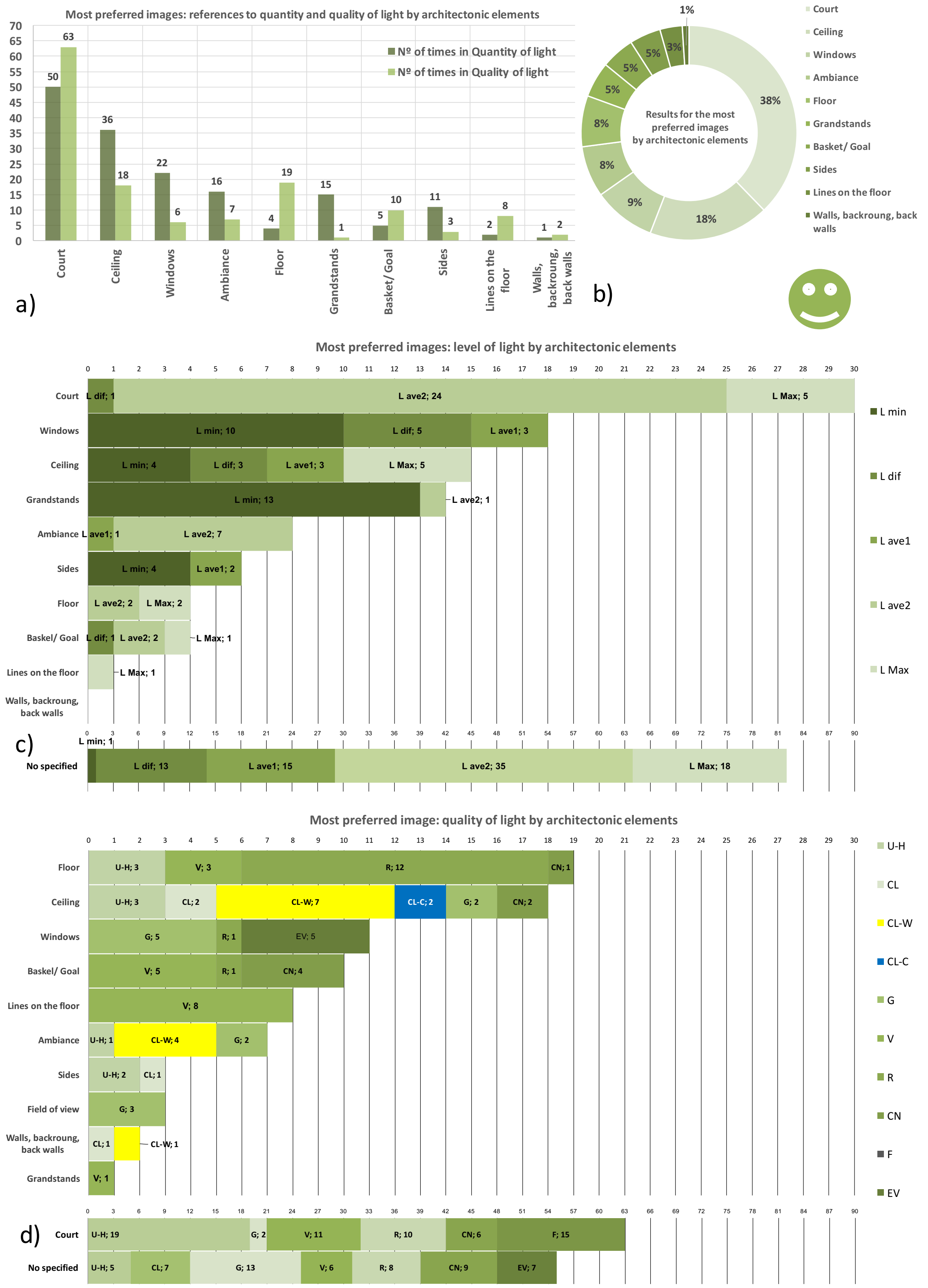


Figure 7-13. Graphics showing the text analysis results about the most preferred images responses.

a) columns chart showing the references to the quality and quantity of light by architectonic features

b) doughnut chart showing the percentages of references by architectonic elements

c) staked bar chart showing the quantity of light category by architectonic features (scale=30 and 90 n° of references): L= light or lighting level, L min=minimum, L dif=diffuse, L ave1=, average, L ave2= good and L Max= maximum

d) staked bar chart showing the quality light category by architectonic elements (scale=30 and 90 n° of references): U-H=uniform, CL=colours (including warm and cold), G=glare, V =visibility, R=reflects, CN=contrast, F=focus

7.2.4 Less preferred images

The results of the rejection responses resulted in a total of 517 units extracted from 302 sentences. The most stated categories are: quantity of light 50%, quality of light 43%, "exterior views", including "no daylight outside" and "other" with 3%, and type of light 1%, see *Figure 7-14*.

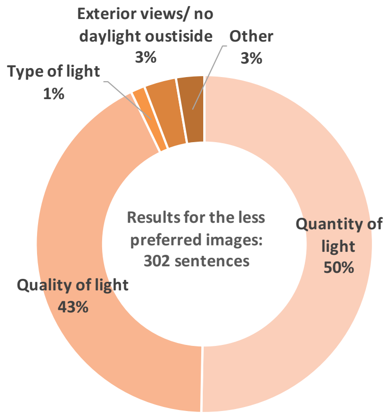


Figure 7-14. *Doughnut chart showing the text analysis of the less preferred images responses by the percentage of the main categories extracted.*

Quantity of light

The themes identified about the level of light are, with 260 units extracted: "no sombre/ /dark, gloomy/black" is notably almost half of the responses with the 44%, and "too direct/strong/bright/aggressive light" with 39%, then followed by "low/minimum" with 12%, not "good/adequate/enough" with 3%, and "lighting level" in general, with 2%, see in Figure 7-*15*.

Quality of light

The most frequent themes in the quality of light are, with 220 units extracted: "no glare/dazzled" with a third of responses with 33% and "no reflects/reflections/light-sun spots" with 28%, followed by "high contrast" with 15%, colour with 11% ("warm/yellow" with 6%, cold/blue" with 3% and "colour" with 2%), "no uniform/homogeneous" with 4%, "no focus" on the court with 4%, "low visibility" 3% and "no contrast" 2%, see Figure 7-*15*. The architectonic elements are the most referred items in quantity and quality of light categories with 53%, and the "no specified/light, lighting" references with the 46%, see Table 7-8.

Architectonic features

The most architectonic features referred are: the "court" with 23%, 62 items (35+27 in quantity and quality of light respectively), followed by floor/parquet and ceiling with 15%, windows 13% (most in quality of light) and 11% ambiance/hall.

The last subcategories identified are: basket/goal, walls/background/back walls, sides, grandstand, glass and blades, as shown in Table 7-8 and detail in Figure 7-*16*.

Type of light, exterior views and others

The last three categories are "no exterior views" with 3%, including "no daylight outside" and "other" with 3%, followed by "natural light" with 1%.

In "other" category, the following references were included as example:

- *"Sentiment d'enfermement"*, FR. Feeling of imprisonment, EN
- *"La diversité des sources lumineuses"*, FR. The diversity of light sources, EN

Most linked items

The most concurrent items in the subject's rejections in the main categories were:

- "shadows, darkness, gloom" in the "court", the "ambiance" and the "ceiling"
- "no reflects, reflections" on the "floor", and in the "court"
- "no glare/dazzled" and "too direct" level of light coming from "windows"
- "no glare/dazzled", "high contrast" and "warm/yellow" colour in the ceiling
- "too direct" light, "no glare/dazzled" in the "basket/goal", "sides" and "walls/background"
- "no focus/accent" on the court

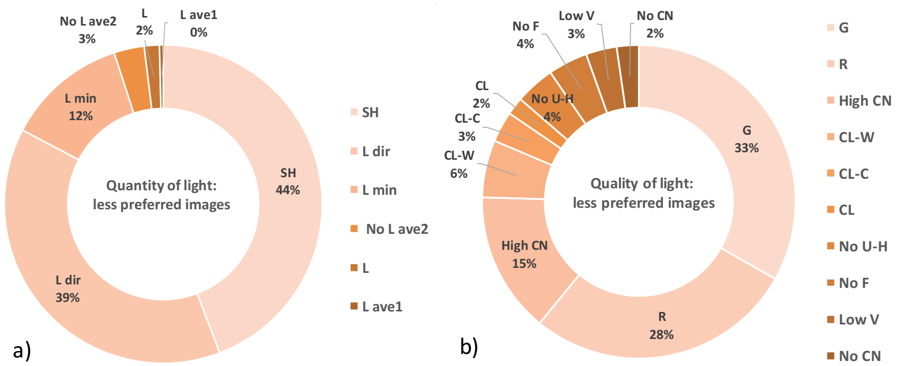


Figure 7-15. *Doughnut charts showing the most referred items in the less preferred images by quantity and quality of light categories.*

a) quantity of light: SH= shadow, dark, L= light or lighting level, L dir= direct light, L min=low light, No L aver2= no good light level, No L aver1= no average level of light

b) quality light: G=glare, R=reflects, High CN=high contrast, CL=colour, CL-W= warm colour, CL-C= cold colour, No U-H= no uniform, No F=no focus on the court, Low No V= no visibility, No CN=no contrast

a)

Most referred categories	Nº of times in Quantity of light	Nº of times in Quality of light	Totals	Percentage %
Architectonic elements	129	138	267	53%
No specified/ Light, lighting	128	102	230	46%
Field of view		3	3	1%
	257	**243**	**500**	

b)

Architectonic elements	Nº of times in Quantity of light	Nº of times in Quality of light	Totals	Percentage %
Court	35	27	62	23%
Floor	6	35	41	15%
Ceiling	17	22	39	15%
Windows	12	23	35	13%
Ambience	25	4	29	11%
Baskel/ Goal	14	6	20	7%
Walls, backroung, back walls	5	9	14	5%
Sides	5	6	11	4%
Grandstands	6	2	8	3%
Glass	3	2	5	2%
Blades	1	2	3	1%
	129	**138**	**267**	**100,0%**

Table 7-8. Tables showing the most referred categories in quantity and quality of light in the less preferred images.

a) architectonic elements, no specified/ lighting, and field of view, b) detail of subcategories in architectonics elements

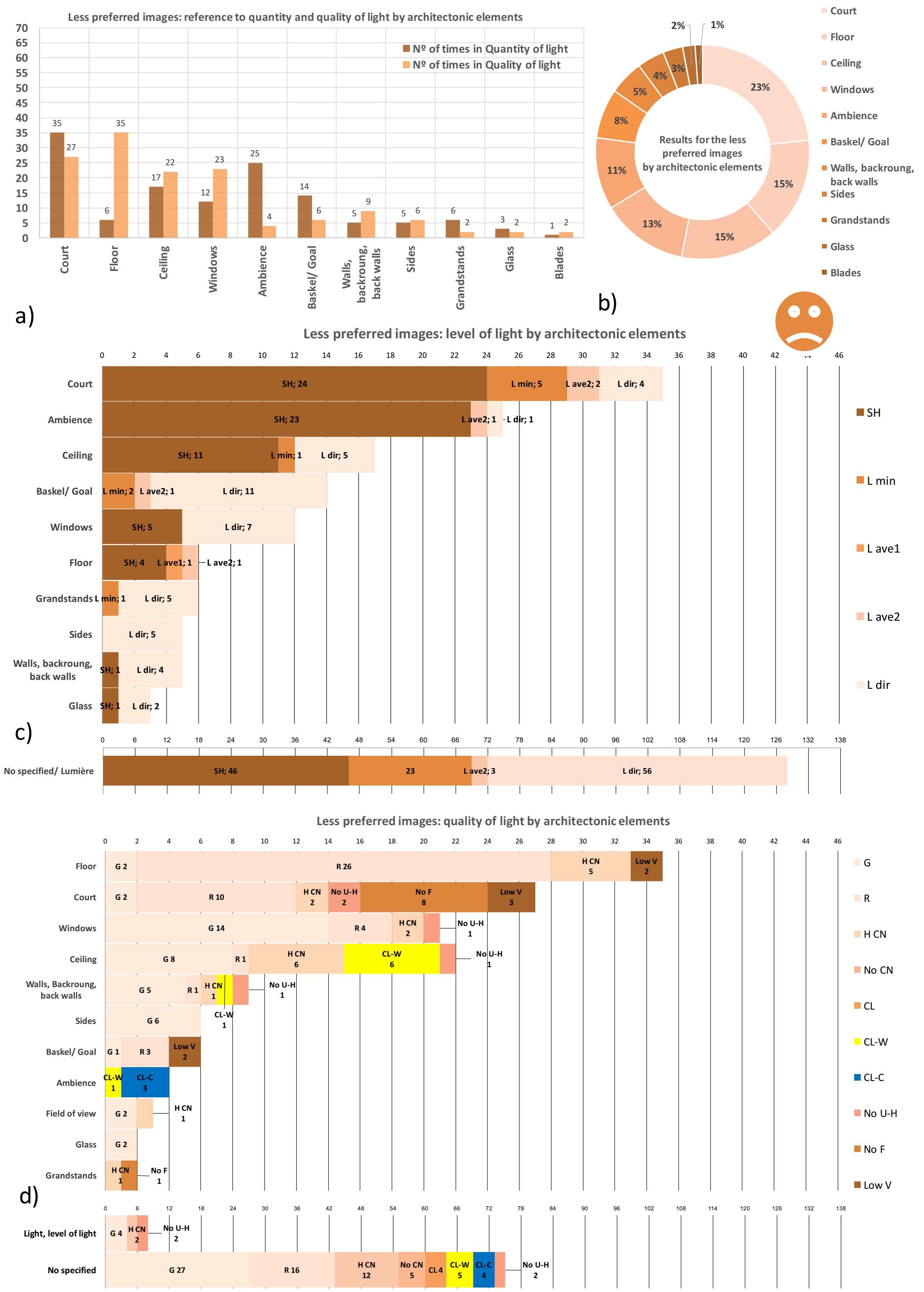


Figure 7-16. *Graphics showing the text analysis results from the less preferred images (rejection) responses.*

a) columns chart showing the n° of times of architectonic features in the quality and quantity of light categories

b) doughnut chart showing the percentages by architectonic elements

c) staked bar chart showing the most referred levels of light by architectonic features (scale=46 and 138 n° of references): L min=minimum, L dif=diffuse, L ave1=average1, L ave2=average2 and maximum

d) staked bar chart showing the most referred quality light characteristics by architectonic elements (scale=46 and 138 n° of references): G=glare, R=reflects, H CN=high contrast, No CN= no contrast, CL=colour CL-W=warm, CL-C=cold, No U-H=no uniform, No F=no focus, Low V=low visibility

7.2.5 Tests experience

Finally, a questionnaire about the whole experience of the test realization was presented to the subjects in the last part of the experiment, that included the following subjects in Figure 7-17.

Level of realism of images' brightness

About if the brightness of the images presented were realistic, the majority of participants stated: "enough realistic" with 63% and "very realistic" with 34%. A small group of 3% considered that the images brightness was hardly realistic 3% and no responses for "not at all realistic".

Dazzled/glare perception during the test

The subjects were asked about if they felt dazzled/glare during the experience. The majority of responses was that they felt slightly dazzled 75%, followed by a small group of very 16%, not dazzled 9%, and no responses for extremely dazzled.

Brightness of the screen

About if the subjects were bothered or disturbed by the high brightness of the screen, the majority indicated "not at all" with 53%, and "slightly bothered" 41%, followed by a small group of "very bothered" 6% and no extremely bothered with 0%.

Physical discomfort due the test

Finally, the panel were asked about if they felt a physical discomfort resulting of the experience, and the majority responded that "no" with the 94% and a small group of "yes" with 6%. The reasons given for explain the physical discomfort were:

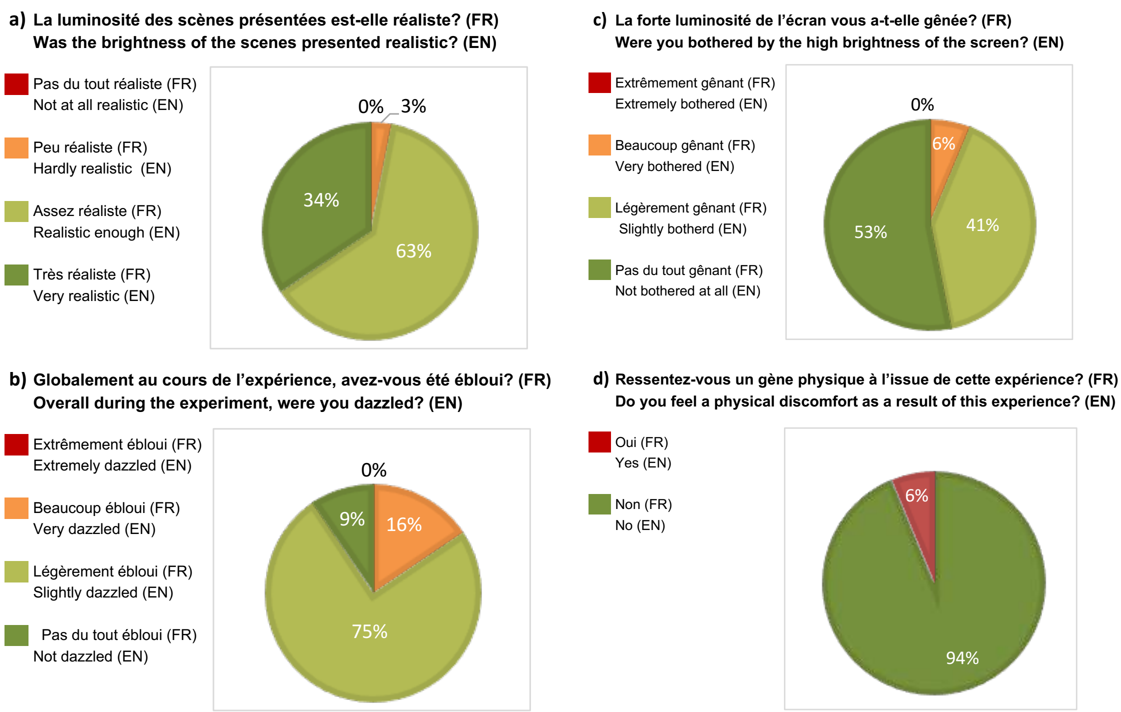


Figure 7-17. Pie charts showing the results of the final questionnaire about the whole experience of the experimental test: original language (FR) and translation by the author (EN).

a) if the brightness of the scenes presented was realistic, b) if subjects were dazzled, during the overall experience, c) if subjects were bothered during the experiment by the high brightness of the screen, d) if subjects feel a physical discomfort resulting of the experience

7.3 Discussion of results

The complete results of the test are included in the Appendix IV section A, pp. 2-53. Following, there is a short summary of the most and the least preferred images to be linked to the quality text analysis results.

7.3.1 Most preferred images

Athlete users

Based in described results of the test, see Appendix IVA, pp. 19-27, and the luminance distribution by False Colour Analysis in *Figure 7-18*, athlete users chose higher and uniform illuminance levels on the court (player area, floor) but without reflections and avoiding high luminance surfaces, mostly from lateral windows, sides and backgrounds. In addition, a uniform luminance levels from ceilings was preferred.

However, in the case of test N°1 CEM EI building, and Test n° 3 INEFC building, two distinct groups were identified. In the Test N° 1 the second group of 7no. participants preferred the high glass transmission coefficient in lateral window, in spite of possible glare, which corresponds to actual real conditions. In the test N°2 the second group of 8no. participants preferred to reduce the contrast of existing conditions, between opaque and glazed squares of the ceiling, which was another type of improvement.

Spectator users

In general, subjects chose again higher and uniform illuminance levels on the court (player area, floor) but without reflections and avoiding high luminance surfaces, mostly from lateral windows, see Figure 7-19.

In addition, uniform luminance levels from ceilings were preferred, with the addition of blades for solar shading devices. Also, the yellow and warm colour over the ceiling was most preferred for Test N° 6.

However, in the case of Test n° 4, INEFC building, where there is a view of the landscape through the window, two distinct groups were identified. The Group 2 of 9 participants preferred the real situation with the high glass transmission coefficient in lateral window and exterior views, in spite of possible glare. Moreover, the images with low transmission coefficient glasses, were perceived by some subjects as night time situation, because they didn't see through the window and as a consequence there weren't exterior views or daylight coming from outdoors.

Level of difficulty for the test realization and comfort

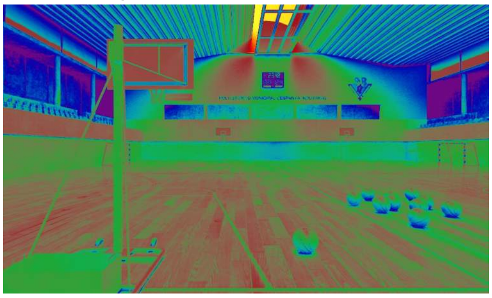
Although the majority of participants stated that the test was "very easy" and "easy' to complete, a third of participants found it was "difficult" and "very difficult". Most of all, the difficulty was because of similarities of scenes evaluated or slight light variations perceived when comparing scenes. This can be explained because small variations of illuminance or luminance could be difficult to detect by participants. For example, measures related to the transmission of glass coefficients. However, other measures were expected to be immediately noticed by subjects, as the case of the change of colour on the ceiling surface (white/ yellow).

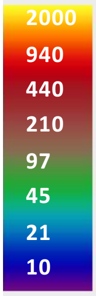
The level of comfort experienced during the test shows a clear correlation with participants that felt very bothered by the brightness of the screen. Additionally, the same positive correlation is with the group of 6% that expressed they felt a physical discomfort due to the experience.

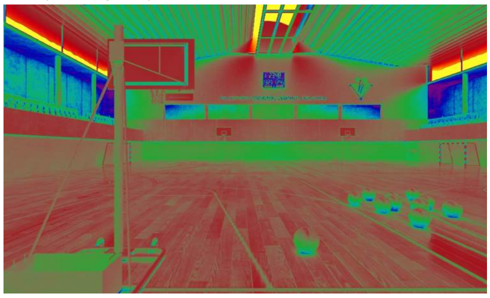
Test results: Athlete

Most preferred images	Less preferred images

Case of study: CEM EI – Test series nº 1. Athlete point of view, group 1 (25 subjects)



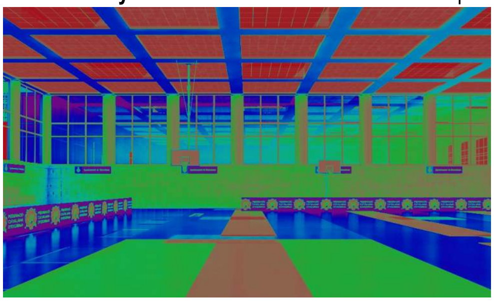


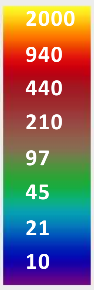


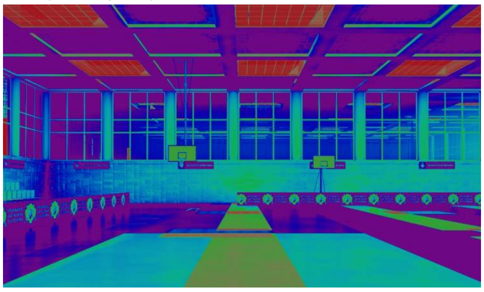
CEM EI- Image 4- Improvement measures in lateral windows: transmission glass coefficient 20%.

CEM EI- Image 1- Reference image, real situation. Lateral windows, transmission glass coefficient 85%.

Case of study: INEFC M– Test series nº 3. Athlete point of view, group 1 (24 subjects)







INEFC- Image 5 - Improvement measures in top lit system: addition of artificial lighting in opaque ceiling surface: 500 luminance level.

INEFC- Image 2 Improvement measures in lateral windows, transmission glass coefficient 20%.

Case of study: CEM VH – Test series nº 5. Athlete point of view (32 subjects)

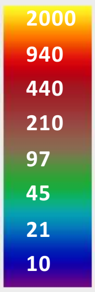
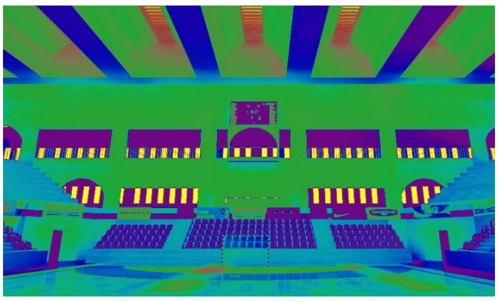
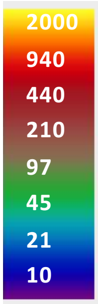


Image 4 - Improvement measures in top lit system: increasing and change orientation of glazing area (0º horizontal, skylight), glazing transmission factor 85%, solar shading device (zenith: 4 Nord and 4 South, orientation 40°). Improvement measures in lateral windows: transmission glass coefficient 60%.

Image 1- Reference image, real situation.
Lateral windows: transmission glass coefficient 85%; interior walls reflection coefficient 19% (orange brick) and solar shading device. Top lit system: orientation of glazing area 90º Nord (Saw-tooth system), glazing transmission factor 50%, and ceiling colour: white.

Case of study: PEG – Test series nº 7. Athlete point of view (32 subjects)





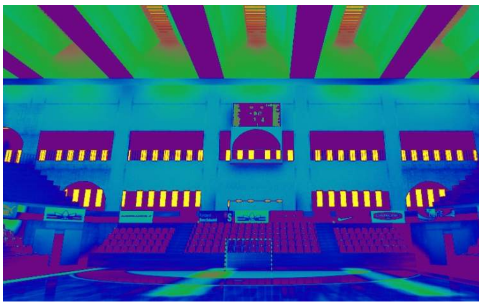


Image 4 - Improvement measures: in ceiling colour white and transmission coefficient 90%.

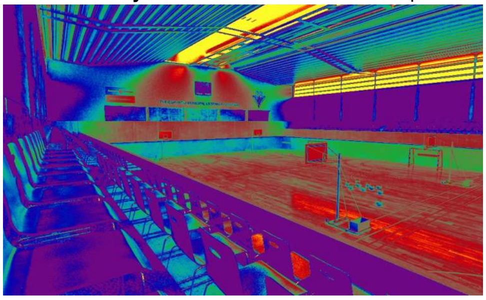
Image 1- Reference image, real situation.
Lateral windows: transmission glass coefficient 85%; interior walls reflection coefficient 70% (white) and concrete walls 20%. Top lit system: skylight, glazing transmission factor 65%, interior of skylight white (85%) and ceiling colour: black (transmission coefficient 2%)

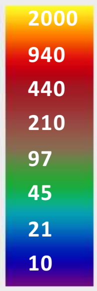
Figure 7-18. Results of the most and less preferred images in False Colour Analysis (cd/m^2): athlete user

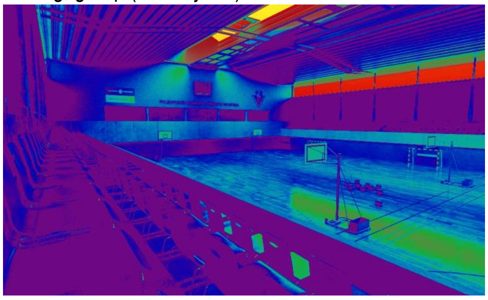
Test results: Spectator and TV broadcasting

Most preferred images	**Less preferred images**

Case of study: CEM El – Test series nº 2. Spectator and TV broadcasting, group (32 subjects)



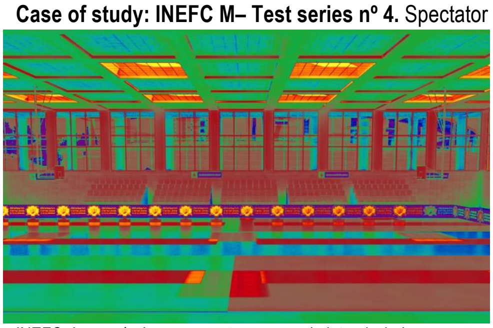


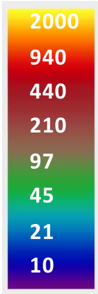


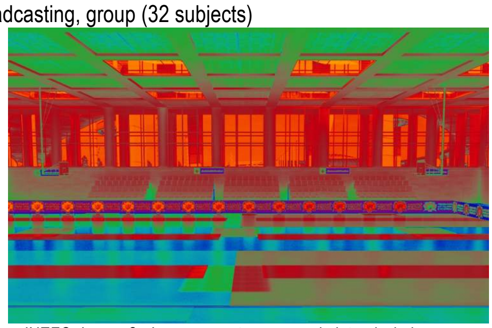
CEM El- **Image 6** - Improvement measures in top lit system: solar shading device (zenith: 4 Nord and 4 South, orientation 40°), increasing glazing area (7,80 width), glass transmission coefficient: 85%. Improvement measures in lateral windows: solar shading device Nord and South (3 blades, orientation 0°)

CEM El- **Image 5** - Improvement measures in top lit system: solar shading device (zenith: 4 Nord and 4 South, orientation 40°), glass transmission coefficient: 85%. Improvement measures in lateral windows: solar shading device Nord and South (3 blades, orientation 0°)

Case of study: INEFC M– Test series nº 4. Spectator and TV broadcasting, group (32 subjects)



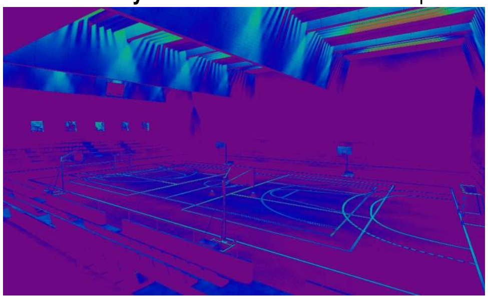




INEFC- Image 4 - Improvement measures in lateral windows, transmission glass coefficient 40%

INEFC- Image 2 - Improvement measures in lateral windows, change of panoramic view (without near exterior elements)

Case of study: CEM VH – Test series nº 6. Spectator and TV broadcasting, group (32 subjects)



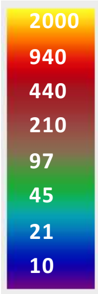


Image 6 - Improvement measures in top lit system: increasing and change orientation of glazing area (0º horizontal, skylight), glazing transmission factor 85%, solar shading device (zenith: 4 Nord and 4 South, orientation 40°), colour of ceiling (yellow). Improvement measures in lateral windows: transmission glass coefficient 20%; interior walls reflection coefficient 85% and colour (white brick)

Image 1- Reference image, real situation.
Lateral windows: transmission glass coefficient 85%; interior walls reflection coefficient 19% (orange brick) and solar shading device. Top lit system: orientation of glazing area 90º Nord (Saw-tooth system), glazing transmission factor 50%, and ceiling colour: white.

Case of study: PEG – Test series nº 7. Spectator and TV broadcasting, group (32 subjects)

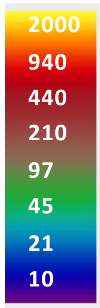


Image 4 - Improvement measures: in ceiling colour white and transmission coefficient 90%.

Image 1- Reference image, real situation.
Lateral windows: transmission glass coefficient 85%; interior walls reflection coefficient 70% (white) and concrete walls 20%. Top lit system: skylight, glazing transmission factor 65%, interior of skylight white (85%) and ceiling colour: black (transmission coefficient 2%)

Figure 7-19. Results of the most and less preferred images in False Colour Analysis (cd/m²): spectator and TV users.

Level of accuracy of the images' brightness

Almost two thirds of participants (63%) said that the brightness of images evaluated during the test were realistic enough, followed by one third stated that they were very realistic (34%).

Brightness of the screen and dazzling experience

During the test experience, almost half of participants felt bothered by the high brightness of the screen 41% and very bothered with 6%. Moreover, almost all participants expressed that they were slightly dazzled (75%) and very dazzled (16%) during the experiment.

Finally, a small group (6%) expressed they felt a physical discomfort due to the test experience, that is consistent with the percentage of respondents who expressed being very bothered by the high brightness of the screen.

7.3.2 Preference and rejection criteria

The results of the most and less preferred images over 1073 units extracted in 572 sentences, show a similar distribution of the five main categories selected: quality of light 45% (most) and 43% (less), exterior views 4% (most) and 3% (less), and others with 2% and 3%. However, a small variance results in the categories of quantity of light 46% (most) and 50% (less), and type of light 4% (most) and 1% (less), as shown in

Figure 7-20.

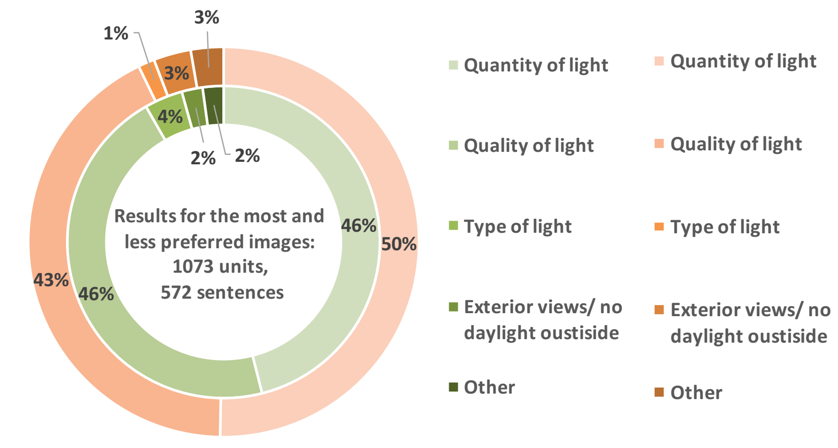


Figure 7-20. Doughnut chart showing the results of the main categories extracted from the total of responses: most preferred images (green) and less preferred images (orange).

Considering the total of the results, more than the 90% of units extracted are about the quantity ("no sombre/shadows/darkness", "light", "good level of light") and quality of light ("no glare" and "no reflects" and "uniform") followed by the type of light and exterior views with 3%.

The "court" was clearly the most referred architectonic feature with 165 references, followed by "ceiling", "floor", "windows" and "ambiance".

Next, the most recurrent ideas extracted from both athletes and spectators' tests are summarized in preferences and rejection criteria.

Most preferred images

The most frequent ideas extracted supporting the images preferences are, in order of occurrence:

- Well illuminated court or playing area (good or enough illuminance level) in the first place, then, followed by other architectonic elements as: ceiling, ambiance, floor and basket/goal area
- Uniformity and homogeneity on the court, in the first place, and for the overall space or ambiance
- An accent light or focalization over the surface of the court was preferred over the rest of the architectonic features, most of all, a low light level on the grandstands, followed by sides and walls and background
- Low and filtered light coming from windows, with exterior views, instead of low transmission glazing coefficients, and no glare
- Good visibility and no reflections in the court and on the floor
- Warm/yellow colours and uniformity on the ceiling
- Natural light most preferred coming from the ceiling/roof, and perceived as "being outdoors"

Less preferred images criteria

The most frequent reasons for the less preferred images or rejection criteria obtained are, in order of occurrence:

- Too direct, strong, bright or aggressive light and too sombre, dark, gloomy, black and poor lighting level, in general, then on the court, followed by the overall space or ambiance and ceiling
- Reflections on the floor, in general and on the court, followed by high contrast
- Glare and dazzled in general, then from lateral windows, followed by ceiling, sides and walls/background
- Too direct, strong, bright or aggressive light in the basket/goal and from windows, followed by ceiling, grandstand, sides and walls/background
- No focus or accent lighting on the court and low visibility of the floor
- Warm/yellow colour in the ceiling, in general, followed by ambiance and walls
- Cold/blue colours, in general, and in the ambiance
- No daylight from windows and no exterior views (low transmission glazing areas, windows), insufficient lighting level, sunlight/daylight

Hints, ambiguity and perception

In general, the reasons for the preference and rejection criteria were clustered in the main categories and latterly in sub- categories, as shown in section 7.2.3. However, some ideas stated or exposed by participants have shown a large variety of hints.

One of the sub-categories or items with more hints were about the quantity of light considered "enough", "sufficient", "well", "good" or average level of light. For example, in a first classification, three different average levels of light or L ave were identified, according to the following:

- Average level of light 1, $L\ ave^{1}$= "*Lumineuses mais pas trop*", FR. Bright but not too much, EN
- Average level of light 21, $L\ ave^{21}$= "*Lumière", "éclairage": "assez", "suffisant"*, FR. Enough, sufficient level of light, EN
- Average level of light 22, $L\ ave^{22}$= "*Lumière", "éclairage": "bonne", "bien"*, FR. Good level of light, well illuminated, EN

In this case, the two last 2 subcategories ($L\ ave^{21}$ and $L\ ave^{22}$) were clustered in the same group as $Lave^{2}$ (Level of light: good, adequate, enough, well) because their significance can be associated.

Others sentences showed ambiguity, that may have led to some kind of contradiction of the first idea. For example:

- "*Surfaces vitrées non éblouissantes avec vue sur le ciel*", FR. Non-glaring glazed surface with a view of the sky view, EN.

With the aim to group some co-occurrences of words, it was counted by the author as: <Non-glaring glazing surface> first idea: "no glare" from "glazed surface" or "windows", (in the context of the test N° 4), <with a view of the sky> second idea: "exterior views" by "windows. In this case, the window was the source of the glare, due to the high luminance of the sky, as shown in the images of the test N°4, Figure 7-19. It could also state that users prefers non-glaring windows with the view of the sky instead of exterior reflexions with potential direct light, as in the next sentence:

- *"Masque blanc ou ciel, je préfère le ciel",* FR. White mask over the sky, I prefer the sky, EN

Sentences, that were clustered in "Other" category, were very descriptive in terms of subjects' perception, but difficult to translate with accuracy due to simplifications by participants writing, including missing words, and to avoid possible bias and misinterpretation by the author. As well, it results in a low occurrence in the analysis, as the examples of sentences below illustrates:

- *"L'image donnant l'impression d'être enfermé",* FR. The image is giving the impression of being indoors/shut away, EN
- "*Certaines images ne semblent pas naturelles",* FR. Some images don't look natural, EN

7.4 Chapter conclusions

The results of the experimental test and the quality assessment of the users' responses provided additional information about which aspects are significant for sports hall users, in terms of the most relevant preferences and dislikes to achieve a comfortable luminous environment.

Users preferences in sports halls

Six broad themes emerged clearly form the qualitative analysis of the open-ended responses: quantity of light, quality of light, architectonic features, type of light, exterior views and other.

Firstly, the amount of light or lighting level or the contrary: too dark, gloomy or sombre, was "per se" a significant factor to decide which environment was the most suitable for the participants.

However, some ideas exposed by participants, such as the level of light or lighting levels, have shown a large variety of hints, e.g.: as "good", "well", "enough" with "but no too much". So, the question about how much is a good lighting level but not too much remains.

Secondly, the results indicate that the court or the playing area surface is the main element in the sport hall users' field of view - FOV, when users are considering to play a sport and/or watch a sport competition. The court has a greater hierarchy and importance over other architectural features, and which must have a good/adequate and uniform/homogeneous level of illumination. This establishes the preponderance of the court and the floor, as the central surface in the sports hall space, over secondary or peripheral components, where a lower and diffuse form of lighting is preferred. These secondary elements are the ceiling, followed by the side windows, the grandstand/seating area, and the walls/background. Likewise, the preferences of users were avoiding glare, the absence of reflections and an adequate contrast on the court, in the first place.

Other ideas stated for preference criteria were the colours, mostly warm and yellow, a good vision or visibility of the details and an accent light on the court, as "theatre lighting", with a minimum light level on the grandstand or spectators seating areas.

Daylighting design strategies and measures

Although the test was performed on a small sample of participants, the findings show that the majority of measures proposed are validated by users, against the existing or real luminous conditions. This suggests that the previous diagnosis carried out was consistent with existing or potential discomfort situations identified. However, this measures must be simulated and tested under clear sky to have full validation in this Mediterranean climate.

Coherence of justification criteria and images selected

Moreover, the ideas extracted by subjects for the most and less preferred images selection are coherent with the results of the test and luminances False Colour Analysis, which supported the selection of the most suitable luminous environments for playing sports or watching a competition for the most.

However, a small number of participants preferred real or actual conditions with some opposing results. This can be explained as two different groups were identified in test N° 1 CEM El - Athlete and N°4 INEFC – Spectator/TV broadcasting, where the existing transmission glass coefficients where chosen, in spite of potential glare from lateral windows.

Another example of opposing or inconclusive results is the measure to change the colour of the ceiling (warm/yellow) that was liked and disliked by participants almost in the same proportion.

Psycho-visual test experience

The results suggested that the level of accuracy obtained by simulated images and the whole test experience was capable to reproduce real conditions of brightness and luminance in the FOV. Also, as a consequence, glaring conditions and visual physical discomfort were experienced by participants, most of all, in the athlete situation.

Validation of design measures

The results obtained in this chapter contribute to the effectiveness and feasibility of daylighting design strategies and measures to improve the visual comfort in top-lit sports halls. From these results, it can be deduced that in sport halls both the level of natural light on the court and the court, as main architectonic element of the space, are considered as key factors in the luminous environment evaluation by users.

Furthermore, these results suggest that toplighting (from ceiling) may be considered the most preferred light source, because it provides uniformity and focus or accent on the field of play, and avoiding glare and reflections from windows and sides.

Likewise, the design measures suggested were validated and preferred by users. Although the analysis of open-ended responses was a challenging task, the results revealed quality information about users' preferences and visual perception in sports halls.

8

Case implementation and validation: the new Palau d'Esports Catalunya

The previous chapter describes the experimental test carried out in four top-lit Olympic sports halls and the most significant results from the quality text analysis from subjects' responses, in both athletes and spectators /TV broadcasting situations.

This chapter summarizes the optimization of natural light and design strategies implementation during the design phases of a new top-lit sports hall: the Palau d'Esports Catalunya in Tarragona. The sport centre was built to host the Tarragona 2018 Mediterranean Games. Later, two monitoring campaigns by Post-Occupancy Evaluation – POE were conducted to verify the effectiveness of the daylight strategies implemented. The skylight optimization and POE campaigns were commissioned by the Consell Català de l'Esport – CCE, Government of Catalonia and the results have contributed to a conference paper (Ortiz et al. 2019), see Appendix IV, section C, pp. 201-236.

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8.1 Implementation of daylight strategies in a new sports hall

This chapter summarizes the design process of the central skylight and the proposal of strategies and measures during the building design of the new sports hall in Tarragona: Palau d'Esports Catalunya – PEC. The optimization of the skylight included daylight dynamic simulations and, based on these, the proposal of measures to achieve a good level of natural light and optimal visual comfort.

This research work was carried out at the Catalonia Institute for Energy Research – IREC during 2015, under the coordination of Dr. Jaume Salom (González Matterson and Salom 2015).

After the new sports hall was built, the theoretical results of the dynamic simulations were contrasted with the results of the visual comfort assessment with Post-Occupancy Evaluation – POE during the building's use, see section 8.4: the first campaign (González Matterson, Salom and Ortiz 2017), and the second campaign (Ortiz et al. 2019), see Appendix IV, section C, pp. 201-236.

Case study: Palau d'Esports Catalunya-PEC

The Palau d'Esports Catalunya - PEC was promoted to be a nearly Zero Energy Building - nZEB by the Consell Català de l'Èsport - CCE, Secretaria General de l'Esport- SGE, Generalitat de Catalunya. Also, it was built to host the handball competitions in the XVIII Mediterranean Games, celebrated in the summer 2018, from 19th of June to 1st of July, see Figure 8-1.

This new sports facility was funded and coordinated by the CCE, SGE, Infraestructures de Catalunya-IC, Government of Catalonia and built during 2016 to 2018. The building design team is UTE Barceló Balanzó Arquitectes SLP + AIA Salazar Navarro Activitats Arquitectoniques SLP.

Collaboration framework

In the framework of the Catalonia Institute for Energy Research-IREC Project "NZEB- Consell Catalá de l'Esport- CCE" the provision of objective information and recommendations were carried out during the building design process of the new sports hall. The aim of this collaboration was to support the design team to achieve a nZEB sports hall, including the optimization of the central skylight for daylighting and to contribute with specific design measures to be included in the design phases and tender documents.

Building design features

The Palau d'Esports Catalunya – PEC, is located in the Mediterranean Ring area in Campclar, Tarragona (41°07'19.3" N, 1°12'19.4" E). The elliptical floor plan is longitudinally oriented North-South. The main entrances are located in the ground level (+0.00m) from the North façade and on the lower ground level (-4.00) from the South façade, see Figure 8-1.

The total gross area of the building is 10,822 m^2 with a maximum height of 15m. Around the court, the two levels of the building are organized (-4.00, +0.00) with a seating capacity of 5,000 spectators. The playing area with 1,920m^2 is on the lower ground level (-4.00m) and allows the layout of up to 3 football pitches in parallel.

The structure is composed by metal trusses and reinforced concrete pillars and slabs. The roof is slightly curved, with a central skylight that was designed and optimized to naturally light the court and considering the visual comfort.

Figure 8-1. Site plan and render of the exterior of the Palau d'Esports de Catalunya-PEC.

Developed design phase (Source: technical documentation, UTE Barceló-Balanzó Arquitectes SLP & AIA- Activitats Arquitectòniques SLP, 2015a): site plan of the Mediterranean ring in Campclar, Tarragona, pp.10, top. Computer generated image-CGI showing the sports hall's features of the premises, South entrance, level -4.00, pp.19, bottom.

The daylighting features

The sidelighting is composed by vertical windows covering all the perimeter of the curved and faceted continuous façade (North, NE, East, SE, South, SW, West and NW). The façade is arranged on 3 levels with different solutions: opaque, transparent and translucent glazing windows, see Figure 8-1. The fenestration varies its glazing material and the brise-soleil, modifying their spacing and orientation to improve the sun protection.

The toplighting system is the central skylight with a flat roof window of 576m2 of surface (12m width x 48m length) and is located in the centre of the roof and symmetrically positioned in relation to the court. The skylight glazing material is translucent.

8.2 Daylight skylight optimization

The main goal of the daylight optimization was to develop and verify the optimal solution for the central skylight proposed by the design team for the new sports hall (González Matterson and Salom 2015) and based on three main objectives:

- To maximize the natural light in the court or playing area with a good distribution (U= uniformity)
- Avoiding direct light/sunlight penetration in the court
- Visual comfort: minimizing glare sources and maintaining a good luminance balance in the users' field of view – FOV for athletes and spectators, including TV broadcasting conditions

8.2.1 Daylighting design strategies

The initial assessment of the design of the Palau d'Esports Catalunya-PEC in the concept and developed design phases, resulted in the provision of high level advice about the following points, see *Figure 8-2*:

- Daylighting systems: a roof window or flat skylight (toplighting) and 3 levels of windows (sidelighting) in a continuous façade to daylight the court
- Skylight glazing surface: translucent glazing area with a low coefficient of Visible Light Transmission-VLT=20%
- White ceiling: skylight well with squared ends and alternative of including a translucent ceiling below the skylight opening
- Shading devices and daylight control: brise-soleils and overhangs for side windows and a movable fabric for the skylight

Assessment of the concept and developed design

The use of the central skylight was considered an appropriate solution to uniformly bring natural light to the sports hall, specially to day-light the court.

The central position of the skylight and the symmetrical relation to the court or playing area were considered as optimal to favour the uniformity of the E_h in the court. However, the skylight performance should be simulated to obtain objective data about the compliance of minimum horizontal illuminance - E_h levels and uniformity - U on the court. This system has also the potential to integrate natural and passive ventilation systems (by chimney effect) in the roof.

The proposed skylight glazing material was verified and adjusted by dynamic simulations to avoid direct sunlight on the court. It was highly recommended to be simulated and to obtain values of Daylight Autonomy - DA%, Maximum Daylight Autonomy - DAMAX%, Useful Daylight Index - UDI%, Daylight Factor - DF% and simplified Daylight Glare Probability - DGP%, including alternatives for glazing materials and a translucent ceiling.

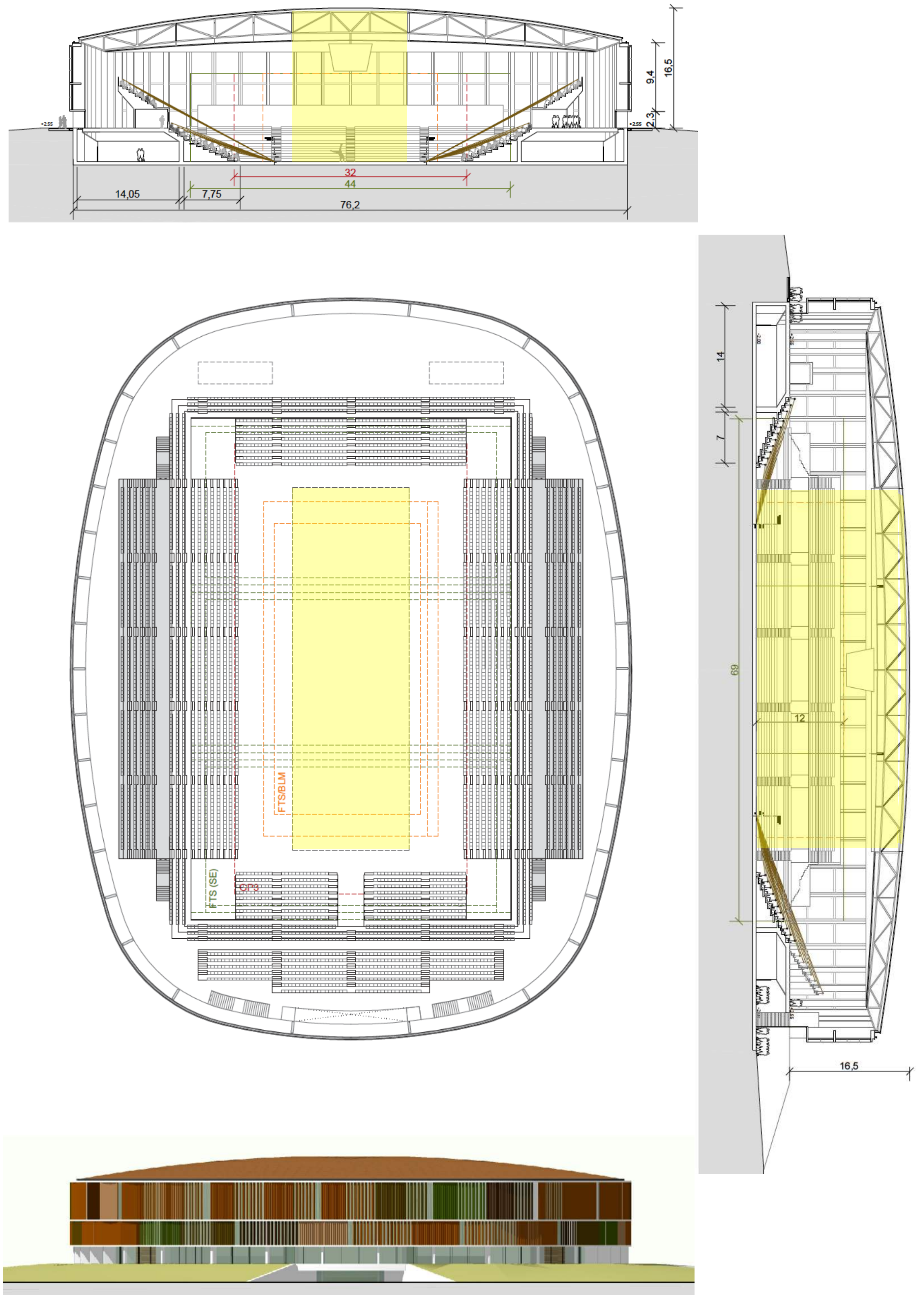

Figure 8-2. Drawings from the developed design phase of the Palau d'Esports de Catalunya-PEC (Source: UTE Barceló-Balanzó Arquitectes SLP & AIA - Activitats Arquitectòniques SLP 2015a).

Drawings form the Developed design phase, the yellow colour is highlighting the relative position of the skylight:

- Floor plan, pp.17, centre.
- Cross section towards North, top.
- Longitudinal section towards East, in pp. 19, right.
- South façade, in pp.13, bottom.

Daylighting strategies were suggested a-priori to simulations, according to the following:

- Skylight opening: to provide an adequate solution to avoid excessive contrast and adaptation level between the glazing and opaque surfaces. Thus, it was advised to modify the geometry of the ceiling to incorporate a splayed transition surface, splayed ends of the skylight well.
- Lateral windows: to consider especially the implementation of effective sunshade devices and daylight controls.
- Minimize the risk of glare: to effectively shield the glare sources as the skylight and windows, to minimize the direct view of daylight openings from the court and seating areas. Thus, diffusers / ceiling baffles were required and would eventually be verified and adjusted by simulations with simplified DGP calculations and DAMAX% to avoid glare sources, excessive contrast and adaptation level.
- Indoor surfaces: to use bright colours and matte finishing of interior architectural surfaces were also recommended to improve the visual adaptation and reduce excessive contrast in the FOV.
- Solar shading and daylight control devices: to introduce both solar shading devices and daylight control elements in the skylight and lateral windows to minimize and, if possible, to avoid glare sources - G_{source} in the court and users' FOV. Black-out screens were requested to be included for both skylight and windows, to shut-down the natural light.

As a result of these considerations, the first daylighting strategy adopted by the design team was the incorporation of a splayed surface in the ceiling and integrating the roof structure as diffusors and baffles. The splayed surface improves the transition between the opaque and the skylight glazing surfaces as shown in Figure 8-3. This measure was included in the baseline model for the next phase of dynamic simulations, see section 8.3 below.

8.3 Dynamic simulations

After the general daylight strategies were proposed, dynamic simulations were carried out to assess the performance of different skylight glazing solutions with the incorporation of diffusers/baffles, according to the following optimization goals:

- To accomplish and verify a good level of horizontal illuminance in the court: Daylight Factor-DF%, Daylight Autonomy-DA% (annual base).
- To verify and achieve a minimum uniformity – U of horizontal illuminance on the court, to perform training and competition sports activities: E_h training > 200 – 300 lx, and if possible E_h competition> 300 – 500 lx up to 1000 lx, depending on the sport and TV broadcasting conditions.
- To avoid direct light, sunlight and sun spots on the court surface by the toplighting system.
- To minimize or prevent glare situations in the court by the toplighting system, through simplified DGP% (Wienold and Christoffersen 2006), although these calculations are designed for static visual tasks in office buildings.

Simulation models

Six simplified 3D models or scenarios assessed by DAYSIM software (NRC- ISE 2012, Version Beta 3.1). The contribution of natural light from windows was not included in the simplified models.

The baseline model contains the proposed central skylight, included in the developed design phase, plus the addition of the transition splayed surface (between ceiling and skylight), high luminance ceiling and translucent glazing with a visible light transmission - VLT =20%, see Table 8-3.

Design solution	Skylight glazing area	Ceiling	Interior diffusors	DA% (300lx)	DA MAX% (300lx)	DF% E_h lx	Uniformity	DGP% simplified
Dynamic simulations results by DAYSIM								
Model 00 Baseline	Translucent glazing surface VLT=20%	High reflectance surface: ≥0.90	-	Min: 65,00 Max: 73,00	Min: 0.00 Max: 36.00	Min: 3.20 Max: 12.70 (100% of sensors ≥2%)		Min: 0.18 Max: 1.0
Model 01	Translucent VLT=20% +Translucent VLT=20%	High reflectance surface: ≥0.90	-	Min: 31.00 Max: 68.00	Min: 0.00 Max: 14.00	Min: 0.90 Max: 4.80 (57% of sensors ≥2%)		Min: 0.18 Max: 0.52
Model 02	Translucent white colour VLT=20%	High reflectance surface: ≥0.90	-	Min: 21.00 Max: 66.00	Min: 0.00 Max: 12.00	Min: 0.80 Max: 4.00 (50% of sensors ≥2%)		Min: 0.18 Max: 0.52
Model 05	Translucent VLT=20%	High reflectance surface: ≥0.90	31 vertical elements (1) with high reflectance surface ≥0.90	Min: 34.00 Max: 71.00	Min: 0.00 Max: 9.00	Min: 0.40 Max: 4.70 Ave: 2.20 (52% of sensors ≥2%)	0.60	Min: 0.18 Max: 0.36
In-situ measurements - 28/07/2017 11:25 -12:05 CEST, clear sky, E_h exterior =91,100lx -11:25h and 99,800lx -12:05h								
Palau d'Esports Catalunya-PEC	Translucent white colour glazing surface VLT=40% (3)	Perforated white ceiling (3)	7 vertical white elements (2), (3)	-	-	Min: 945 Max: 4,188 Ave: 2,466 Min: 1,742* Ave: 3,094*	0.56* *centre of the court (20mx40m)	HDRI survey results

Diffusors/baffles: (1) 7m height, 2m spacing between them; (2) 7m height, 6m spacing between them; (3) technical documentation.

Table 8-1. Table containing a summary of the simulations results and horizontal iluminance level - E_h obtained in-situ. The most suitable solutions are highlighted in green: the model 05 with 31 vertical baffles has the maximum DA% values and the minimum DA_{MAX}% DPG% values.

8.3.1 Daylighting design measures proposal

Considering the simulations results in terms of Daylight Factor- DF%, Daylight Autonomy- DA%, Maximum Daylight Autonomy- DA_{MAX}% and Daylight Glare Probability-DGP%, specific recommendations and daylight measures were proposed and discussed, with the aim to be integrated in the developed design and construction phases (González Matterson and Salom 2015).

The complete list of measures suggested is shown in Table 8-3. This table also shows if measures were integrated into the design phases, partially or not, the specific technical solution adopted and in which phase of the design project they were included.

Active controls for the artificial lighting system are also recommended. The incorporation of on/off motion sensors and photocells to dimmer the lighting level according to daylight availability showed potential annual savings from 5% up to 22% of the electricity demand.

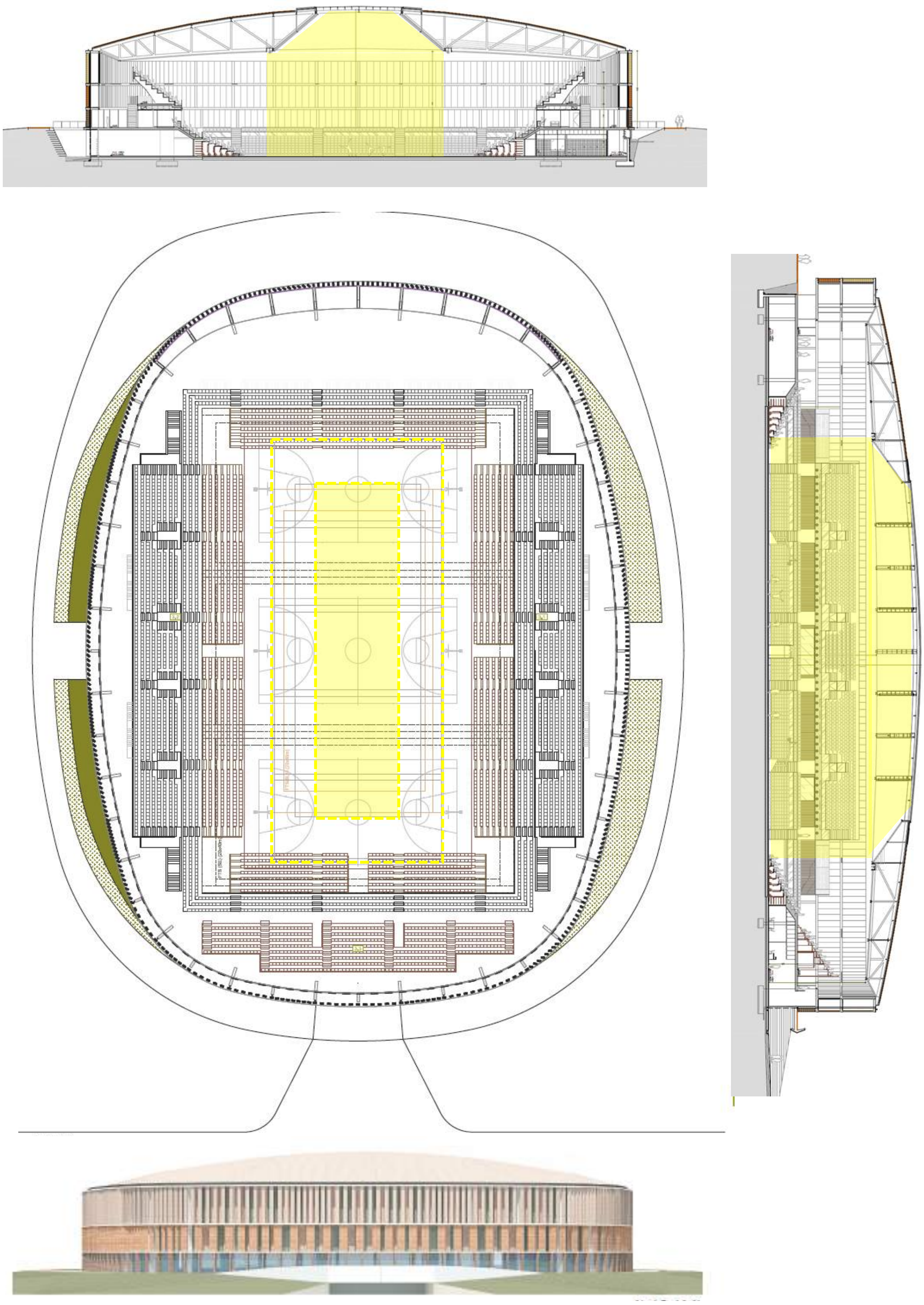

Figure 8-3. Drawings from the technical design phase of the Palau d'Esports Catalunya-PEC (Source: UTE Barceló-Balanzó Arquitectes SLP & Activitats Arquitectòniques SLP 2015b)

Drawings from the technical design phase, the yellow colour is highlighting the relative position of the skylight: floor plan, centre, and cross section towards North, top. Longitudinal section towards the East, right, South façade, bottom.

The cross sections show the modification of the ceiling geometry and the incorporation of 7no. vertical white baffles, according to the recommendations formulated during the developed design and technical design phases. The baffles were made by cladding the steel trusses. The integration of a transition splayed surface between the ceiling and the skylight glazing surface and vertical baffles improved the adaptation by shielding glare sources and avoiding hard frames between the glazing area and ceiling.

8.4 Post-Occupancy Evaluation-POE

The POE evaluation was composed of two different phases of measurements to obtain objective and subjective data about the achievement of targets for nZEB sport hall and the daylight optimization of the skylight:

- The 1st monitoring campaign was focused on the visual comfort assessment by in-situ measurements (González Matterson et al. 2017)
- The 2nd campaign was focused on the thermal comfort, the air quality and environmental survey evaluation, including spectators visual comfort (Ortiz et al., 2019) see Appendix IV, section C, pp. 143-150

8.4.1 1st campaign: visual comfort by in-situ measurements

These measurements were carried out in the last phase of the construction works of the Palau d'Esports de Catalunya-PEC sports hall and before the realization of the Games. The measurements were taken on July 28th of 2017 (summer), under clear sky conditions, from 11:25h to 15:05h (UTC/GMT+1, CEST, Daylight Saving Time), see Table 8-2.

Data obtained	Date	Time period	Artificial Lights
1st campaign: Visual comfort by in-situ measurements			
Eh	28/07/2017	11:25 - 12:05	off
HDRI survey	28/07/2017	13:00 - 15:05	off
2nd campaign: Visual comfort by users' survey			
Visual comfort survey	29/06/2018	18:02 - 19:11	on
	30/06/2018	10:00 - 13:15	on
	30/06/2018	18:11 - 21:15	on/TV
	01/07/2018	10:51 - 13:55	on/ TV

Table 8-2. Table containing the date, time period and artificial lighting conditions during the 1st and 2nd Post Occupancy Evaluation - POE campaigns.

E_h horizontal illuminance

The total exterior E_h was registered at the same time than E_h at indoors, and without obstructions on the roof of the building, from 91,100 lx at 11:25h to 99,800 lx at 12:05h.

HDRI survey

The HDR images were taken by video photometer and digital reflex camera to cover the athletes and spectators/TV broadcasting visual field of view - FOV, see Figure 8-5, .

For the potential glare source assessment, three 3 regions of interest are established in the Field of View – FOV (Inanici 2005b), see Figure 8-6 and Figure 8-7.

The average luminance values of each region were calculated and luminance thresholds were identified for each image with the LMK Laboratory software (TechnoTeam 2015, Version 15.6.23), according to Findglare (Ward 1993). The resulting HDR images are displayed with False Colour Analysis with luminance – L values, see Figure 8-6 and Figure 8-7.

8.4.2 Visual comfort survey: 2nd campaign

The second campaign was realised during the realization of the Tarragona 2018 Mediterranean Games and was focused on thermal comfort and air quality. The results include 140No. visual comfort spectators' surveys.

Users' visual comfort survey conditions

Most of the days were with clear sky with maximum levels of solar radiation. Note that the survey responses were obtained during the handball semi-finals and finals competitions, which took place during daytime and evening (from June 29th to July 1st of 2018). These competitions were TV broadcasted. As a consequence of that the artificial lighting was turned-on, according with the TV and international completion requirements, see Table 8-2.

8.5 Discussion of results

8.5.1 Integration of daylight strategies and measures

The majority of strategies and measures suggested during the skylight optimization process were fully or partially incorporated by the design team in the design phases of PEC, as shown in Table 8-3.

The strategies and measures were based on previous results discussed in Chapter 5 and best practices. These were implemented in the early phases of the design, e.g.: the incorporation of transition splayed surfaces between the skylight and ceiling.

However, other specific measures required verification and were adjusted by simulation results. These were implemented in the technical design and bidding documentation, e.g. the skylight transmission coefficient and number of vertical baffles.

In general, all measures simulated and technical specifications suggested were included without modifications in the building design. Others differed from specified, such as the VLT% of the skylight glazing material and the number of vertical baffles/diffusors included.

8.5.2 Post Occupancy Evaluation-POE results

The results from the two campaigns are summarized according to the different information obtained (González Matterson et al. 2017; Ortiz et al. 2019).

In general, the goals of the daylight optimization were achieved and verified, according to the following:

- Good levels of horizontal illuminance and uniformity on the court.
- No direct light and sunlight penetration, plus no sun patches or sunspots in the court.
- Good distribution of luminances and low risk of glare situation in the users' FOV.
- Spectators survey: perception of lighting level as "Neutral" and "Slightly Intense" by the majority of spectators' users, showing the visual comfort is achieved.

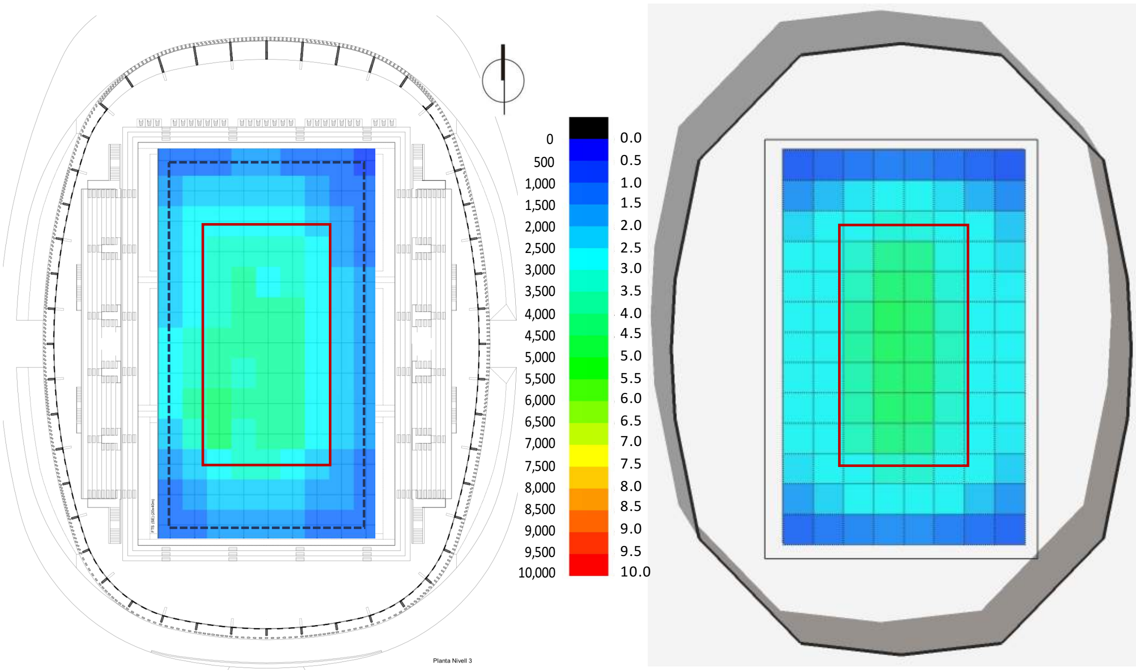

Figure 8-4. Floor plan of PEC showing the results of E_h measurements of the 1st Visual comfort campaign-POE [left] and simulation results by DAYSIM software [right] (Source: González Matterson, Salom and Ortiz 2017, pp.12,30).
E_h horizontal illuminance level (lx), left. Daylight Factor DF% resulting of the model 05 right.
The scale of the measurements is 0-10,000lx and the scale of DF% are 0.0-10.0%, in red rectangle the central area of the court 20x40m

Figure 8-5. HDR images obtained in the 1st Visual comfort campaign-POE from users' viewpoints (Source: González Matterson, Salom and Ortiz 2017, pp.19,21,25, 26).
Spectator point of view: from the grandstands (+0.00) towards the South, top-left, and towards the East, top-right.
Athlete point of view: from the court (-4.00) towards the North-East, bottom-right, and towards the skylight, bottom-left.

Requirements	Design strategies	Objectives	Project	Daylight measures proposed	Strategies and measures implementation		Design phase
Quantity of light							
Minimum E_h illuminance level, and **E_h Uniformity on the court/** playing area	**Increasing daylight admittance** and **illuminance uniformity**	A. Maximize sky dome aperture- θ	Central skylight	A-0 Flat skylight *All simulation models	Yes	Flat skylight: 12mx48m, Total surface=576m2	2, 3, 4
		B. Maximize glass transmission factor	Translucent glazing area	B0-Translucent VLT=20% *Model 00 baseline	Yes	Translucent glazing VLT=20%	2
				B1- Translucent white colour VLT=20%, *Model 02	Yes	Translucent polypropylene white colour VLT=40%, 1000x1000mm, ACIEROID-LUX	3, 4
Quality of light							
Minimizing absolute glare, **adaptation glare,** and **dark and gloomy perception of the luminous environment**	**Integrating solar shading devices**: • obstructing, • reflecting, and re-directing direct daylight	C. Adding internal/external shading devices and black out systems	Central roof light/ skylight	CI.0-Solar shading devices/ blackout system (movable)	Partially	Mobile screen of Fiberglass double-sided PVC coated	2, 3
			Side Windows	CII.0 Solar shading devices (static) and overhang	Yes	Brise-soleil: variable spacing of vertical ceramic blades 50x51 mm, colour variable FLEXIBRICK system	2, 3, 4
		D. Adding internal/ external louvres/ baffles	Central roof light/ skylight	D0- No Internal baffles/diffusors *Model 00 baseline	Yes		2
				D1-Internal vertical baffles/diffusors ≥0,90 reflectance coefficient: 31 elements *Model 05	Partially	Internal white vertical diffusors, coated with perforated PLADUR board: 7 elements (structural trusses)	3, 4
	Reducing glare sources: • filtering + • diffusing daylight • openings out of sight	E. Decreasing glass transmission factor	Central roof light/ skylight	EI.0-Translucent VLT=20%, *Model 00 baseline	Yes	Translucent glazing VLT=20%	2
				EI.1- Translucent white colour VLT=20%, *Model 02	Yes	Translucent white glazing=B1	3, 4
			Side windows	EII.0 Translucent glazing	Yes	Translucent cellular polycarbonate 40 mm	2, 3, 4
	Reducing excessive contrast and improving luminance uniformity: • increasing internal reflections, soften hard frames	F. Increasing reflectance factors + colours	Ceiling	FI.0-High reflectance surface: white ≥0.90 reflectance *All simulation models	Yes	Translucent micro-perforated white fabric, polyester with a double-sided PVC coated	3, 4
			Side walls, background	FII.0-Light coloured surfaces	Yes	White, grey, wood, beige	3, 4
		G. Adding splayed intersections	Central skylight/ ceiling	G0- Square ended skylight well: no splayed	Yes	Fabric white ceiling	2
				G1-Splayed ended skylight well: sloped transition between skylight and ceiling and structure *All simulation models	Yes	Translucent white ceiling=B1, >28% perforation on sloped areas	3, 4

Design phases: 1- Concept design; 2- Developed design; 3-Technical design; 4- Construction

Table 8-3. Daylight design strategies and measures proposal for the skylight optimization of the Palau d'Esports Catalunya - PEC, during the design phases in 2015.

The table shows the relation to the strategies/measures proposed during the skylight optimization process extracted from technical documentation (Source: UTE Barceló-Balanzó Arquitectes SLP & Activitats Arquitectòniques SLP 2015a; 2015b; 2016) showing:

- the correlation with simulation models, if it corresponds
- if measures were integrated in the PEC design phases: yes, partially or not
- which specific technical solution was adopted and in which design phase the daylight strategies/measures were included: 1-Concept design, 2-Develop design, 3-Technical design and 4-Construction

Illuminance levels and uniformity in the court

The E_h horizontal illuminance levels measured shows that the 99% of the grid points on the court exceeds the minimums for training (>300lx), and competition conditions with more than 1,000lx in the total court surface, with E_h minimum=1742lx. Moreover, a good E_h uniformity of 0.56 is achieved in the central zone of the playing area (20m x 40m), as shown in Figure 8-4.

POE correlation with simulation results

Although the 3D models are not totally corresponding with the built sports hall (e.g.: contribution of natural light by windows and different number of vertical baffles), both results obtained in-situ and simulated show to be consistent with daylight distribution patterns in the court. The E_h in-situ measurements are not comparable with the DF% obtained by dynamic simulations. However, similar illuminance levels were verified in terms of maximum, average and minimum values, taking into account the exterior E_h measurements obtained on the roof without obstructions, under specific conditions (91,100 - 99,800lx), see Figure 8-4.

HDRI and luminance survey

The HDRI survey suggests that there is a good distribution of luminances in the court and users' field of view - FOV of both: athletes and spectators/remote spectators and TV broadcasting. There is no direct sunlight penetration in the court and no sunspot or sun patches in the floor surface of the court. There is also a good distribution of luminances, mostly in the areas 1 and 2 of the users' FOV on the floor, ceiling, side walls and background.

However, potential glare sources were identified, which could cause excessive contrast and adaptation level in specific view directions, according to the following:

- Athlete: the view of side windows, mainly towards North, South-West and South, in particular the lower level of the glazing (+0.00), when the openings are in the central area of the FOV. Moreover, there is a direct view of the translucent surface of the skylight, but the potential glare situation is less frequent and probable, due to the peripheral position of the skylight in the athlete's FOV or background, see Figure 8-6. Although the upward view, towards the skylight or ceiling is less frequent in the majority of sports, it could be a potential glare source for athlete users.
- Spectator and remote audience /TV broadcasting: the view of side windows mainly towards North, and South, in particular, the lower level of the glazing (+0.00), due to the central position in the FOV. The view of the skylight could also be a potential glare source, due to the glazing position respect to the external perimeter of zone 2 spectator's FOV (near surrounding), see Figure 8-7.

Spectators' visual comfort surveys

The results of all the surveys indicate that the visual comfort is achieved for the majority of respondents, as the overall illumination is considered "Neutral" with 64% of the total, followed by the 30% of "Slightly intense", see pie chart in Figure 8-9.

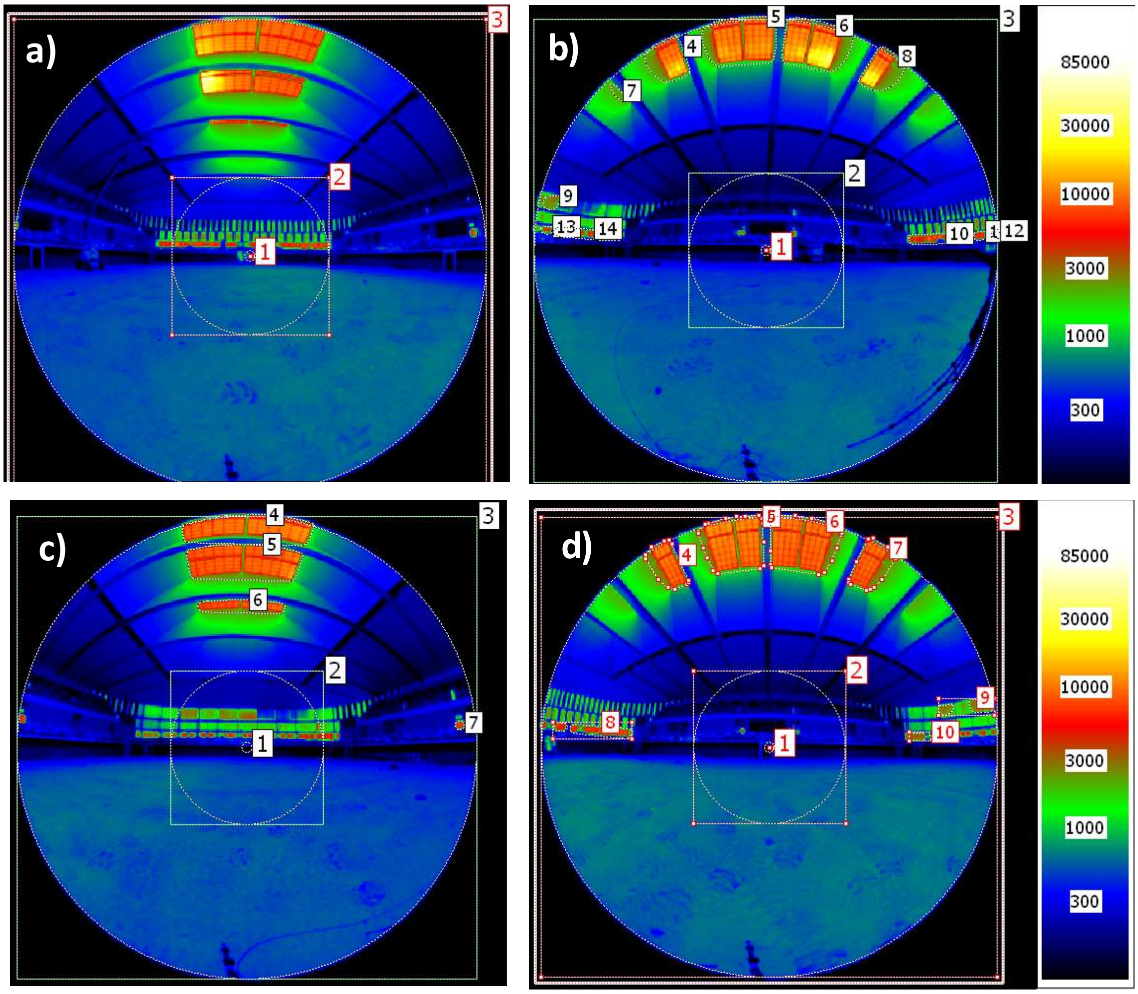

Figure 8-6. HDR images with False Colour Analysis, obtained in the 1st Visual comfort campaign of the POE: athlete point of view (Source: González Matterson, Salom and Ortiz 2017, pp.15-18).

Athlete point of view from the middle of the court: a) towards South, b) towards West, c) towards South, d) towards East. The areas numbered from 4 to 14 have been identified as glare sources - G_{source}. Scale of luminances: 0 - 85,000cd/m^2.

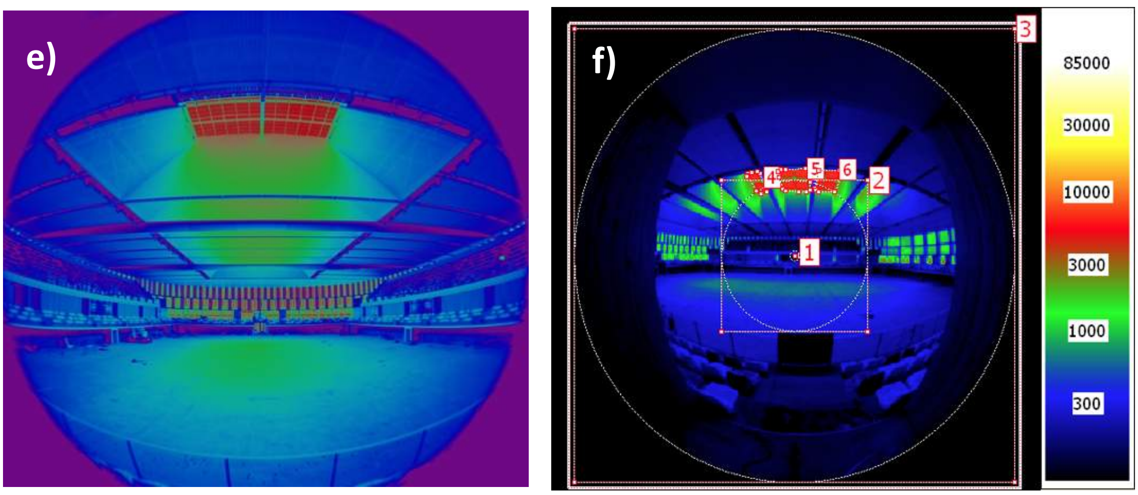

Figure 8-7. HDR images with False Colour Analysis obtained in 1st Visual comfort campaign of the POE: spectator/TV point of view (Source: González Matterson, Salom and Ortiz 2017, pp.23, 26).

Spectator/TV broadcasting point of view: e) from the North grandstand towards South, left, f) from the East grandstand towards West, right. The areas numbered from 4 to 14 have been identified as glare sources - G_{source}. Scale of luminances: 0 - 85,000cd/m^2.

29/06/18 17:30 (CEST): Handball women's semi-finals

30/06/18 10:00 (CEST): Handball men's 7th and 8th positions

30/06/18 20:00 (CEST): Handball women's final

1st/07/18 10:00 (CEST): Handball men's final

Figure 8-8. Images obtained during the 2nd campaign of the POE: Visual comfort survey (Source: photos by Joana A. Ortiz – IREC, 2018, and Ortiz et al. 2019 pp. 4)

The images show the conditions of handball semi-finals and finals competitions according with the surveys' responses obtained. Matches with highest spectators' occupancy levels: 30/06 at 20:00 (women's final) and 01/07 at 10:00 (men's final). Matches with lowest spectators' occupancy levels: 30/06 Morning and 29/06 Afternoon.

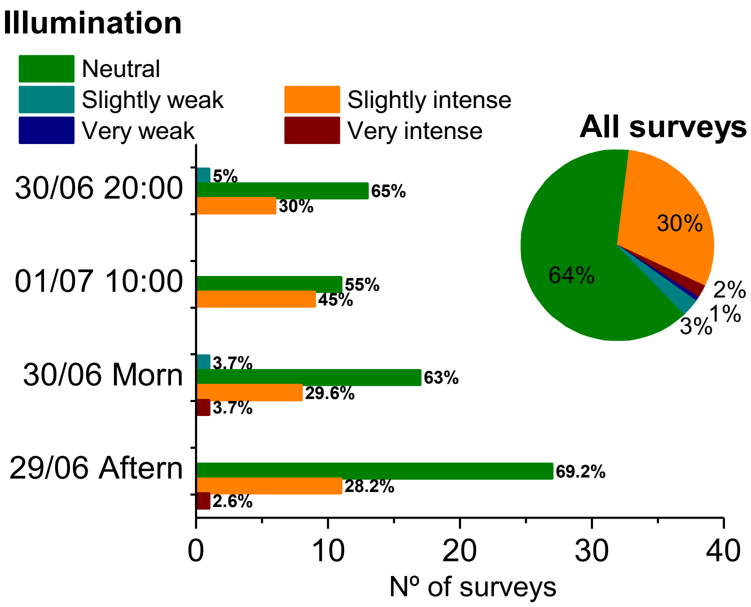

Figure 8-9. Bar and pie charts showing the results obtained during the 2nd campaign of the POE: Visual comfort survey (Source: Ortiz et al. 2019 pp. 5)

The pie chart shows the spectator responses results of the visual comfort responses for the whole surveys, and the bar charts show the results by match: highest spectators´ occupancy levels on 30/06 at 20:00 (women's final) and 01/07 at 10:00 (men's final), and lowest spectators' occupancy levels on 30/06 Morning and 29/06 Afternoon.

The proportion of the responses follows the same trend during the daytime, with the exception of the 1st of July, where the "Neutral" responses decrease to 55% and "Slightly intense" increases up to 45%, see bar charts in Figure 8-9. One likely explanation could be that on that day the handball Men's final competition was held. This competition was televised, so the artificial lighting was turned on to guarantee optimal conditions for the TV broadcasting and maximum lighting levels in the court. This situation, plus the contribution of natural light (10:00 morning) with clear sky conditions, could explain the rise of "slightly intense" perception by the interviewed spectators.

8.6 Chapter conclusions

A series of recommendations and measures to maximize daylight and visual comfort in Mediterranean climate were proposed during the building design and construction of the new Palau d'Esports de Catalunya - PEC building in Tarragona, see Figure 8-10. Some of them were adjusted by dynamic simulations.

Post Occupancy Evaluations – POE were completed to assess the fulfilment of natural lighting design goals and to identify additional measures to improve its operation. Two monitoring campaigns were carried out during the construction and the realization of the Tarragona 2018 Mediterranean Games. The aim was to validate and measure the achievement of general nZEB objectives and in particular, to measure natural lighting levels on the court, visual comfort and users' visual perception.

Considering the approach and the methodology proposed for this research, in-situ E_h measurements, HDRI survey and spectators' visual comfort responses were obtained in real conditions of use. Design strategies integrated for toplighting performed well, in terms of quantity and quality of natural light. However, the conditions evaluated by monitoring campaigns are specific and cannot be extrapolated: e.g. hour, day, month, sky conditions, level of play and artificial lighting.

Daylighting design strategies and measures validation

The majority of the daylighting strategies and measures proposed during the skylight optimization process were fully integrated in the technical design, bidding documents and construction phases of the new sports hall.

The monitoring results have provided objective and subjective evidence about the suitable performance of daylighting strategies implemented. Their contribution was verified, in terms of quality and quantity of light, as follows:

- To achieve good illuminance levels and uniformity on the court, avoiding sunlight penetration for: training, international competition and TV broadcasting levels of play.
- To provide visual comfort conditions, minimizing glare sources, excessive contrast and adaptation level in the FOV, for both users: athletes and spectators/TV broadcasting.

The findings suggest the importance to integrate daylighting design strategies and measures in the early stages of building design to achieve optimal solutions. The impact of the architectonical daylighting and design strategies could have also beneficial repercussions in the quality of the indoor environment, although these intangibles are not addressed in this work, see Figure 8-10.

Figure 8-10. Images of the Palau d'Esports Catalunya-PEC after the Mediterranean Games inauguration in 2018. View of the skylight, top (Source: www.bbatquitectes.com/en, photo by Simon García[1]). View of the court towards the North-East, centre (Source: Palau dEsports Catalunya, que se estrena en los Juegos Mediterráneos de Tarragona by Joan Revillas[2]). View of the court during the handballs finals, the Tarragona 2018 Mediterranean Games, bottom (Source: http://www.aia.cat, photo by Simon García[3]).

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1 Available at: http://www.bbarquitectes.com/es/work/equipamiento-deportivo-juegos-del-mediterraneo-tarragona-2017/ [Viewed: 04/09/2019]

2 Hernández, O. (2018) `*Tarragona se renueva con unos juegos sin derroche*´, El Periodico, Tarragona [ONLINE], 21st of June, 21:33. Available from: https://www.elperiodico.com/es/sociedad/20180621/tarragona-juegos-mediterraneos-sin-derroche-6899684) [Viewed: 04/09/2019]

3 Available from: http://www.aia.cat/projectes-arquitectura/poliesportiu-a-camp-clar/?lang=en [Viewed: 06/05/2020

Methodology implemented

The HDRI survey showed the complexity to objectively evaluate the visual comfort conditions in sports halls, considering multiple users' viewpoints and view directions and carried out before the building inauguration. Specific view directions and viewpoints were selected to consider the users' FOV, following to the methodology previously proposed and tested for this research work.

POE campaigns results

The POE campaigns results demonstrate an adequate performance of toplighting, although the results of the 1st and 2nd campaigns are limited due to specific conditions of measurements. The findings show also a good performance of the top-lit court even during the summer in this Mediterranean climate, with maximum values of global and horizontal solar radiation.

Dynamic simulations

Considering daylighting levels, the in-situ results show to be consistent with dynamic simulations, although the limitations of simplified model calculations, e.g.: no natural light contribution by windows, number of internal baffles, annual based calculations vs. specific conditions of measurements.

Level of play: international competitions

The surveys completed by spectators demonstrate that visual comfort was achieved during the realization of the Mediterranean Games, such as the semi-finals and finals of international competitions. Likewise, it was also accomplished under both natural and artificial lighting.

Significantly, the lighting levels and visual comfort were achieved with the contribution of the natural light, even with international TV broadcasting requirements. However, athletes' visual comfort surveys should be performed for a complete assessment of sports halls users.

Finally, the POE campaigns results have provided both objective and subjective data about the fulfilment of the daylight optimization goals of the new Palau d'Esports Catalunya and during the Tarragona 2018 Mediterranean Games. However, further POE campaigns in different conditions of use (day, month) and level of play might be required to extend these conclusions on annual performance base.

Although the global performance of the building is not a matter of this research, the findings suggest that the initial nearly Zero Energy Building - nZEB design targets were also achieved, considering thermal comfort and air quality.

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9

Conclusions

The previous chapter discussed the procedures performed for the optimization of daylight in a new sports hall, the Palau d'Esports Catalunya. The results of Post Occupancy Evaluation - POE campaigns carried out during the 2018 Mediterranean Games were also discussed.

This chapter presents the conclusions, including the key findings and contributions of this research. Future research work is defined, taking into account limitations and in-line with subjects not addressed in this study. Finally, personal comments and an epilogue are included at the end of the chapter.

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The main goal of this study was to investigate the contribution of natural light in sports halls in Mediterranean climates in relation to both users, athletes and spectators/remote spectators, including television broadcasting requirements. In addition, the impact of daylight design strategies to achieve visual comfort was explored.

Because the athletes and their visual targets are in movement, the visual field becomes three-dimensional and its assessment complex. Thus, a specific methodology was designed and developed for this research, from an architectonic and holistic approach.

Derived hypotheses and additional objectives were established, considering the particularities of sports users and sports halls as a building typology, to evaluate the following aspects:

- the performance of toplighting compared with sidelighting systems
- the most effective daylighting measures to improve visual comfort and their validation
- the preferences of users for comfortable visual environments

9.1 Conclusions

This research was developed in three main parts and completed over several years. After the discussion of results, general and particular conclusions are presented in the following points.

Suitable performance of top-lit sports halls: daylighting levels and uniformity

The first part of this work evaluated the performance of naturally lit and, in particular, top-lit sports halls built for the Barcelona 1992 Olympic Games. Thirteen different sport buildings in Catalunya were assessed, by correlating the widespread use of skylights for daylighting. During daytime, minimum levels of horizontal illuminance and uniformity for training were fulfilled without the contribution of artificial light. However, rooflights and sawtooth facing North were verified as providing too low illuminance levels. Daylighting levels and uniformity for competitions and TV broadcasting requirements were also achieved in the new Palau d'Esports Catalunya. These results suggest the suitable global performance of daylighting and toplighting.

Suitable performance of top-lit sports halls: low risk of glare and adaptation

The preliminary and detailed assessments (Chapters 5 and 8) have shown that toplighting provides a good performance, considering the low risk of glare and adaptation level in the field of view - FOV. Nonetheless, visual discomfort issues by absolute and contrast glare were identified because of lack of daylight control and solar protection devices, among others. Existing and potential discomfort situations were identified for users, mostly originated by sidelighting. Absolute glare with 2,000 cd/m^2 threshold were verified in the most sensitive areas of users' visual field of view –FOV, predominantly from windows. Windows also caused adaptation glare by excessive contrast of luminances. In second place, potential glare and glare sources were verified from rooflights but in peripheral areas of the FOV.

Toplighting can be more suitable than sidelighting in sports halls

The use of toplighting systems in sports hall buildings is more suitable than sidelighting, since they make possible to better uniformly day-light the court, in terms of quantity and distribution.

Toplighting also provides better control of absolute glare, glare sources and adaptation level in the visual field for both athletes and spectators. This is mostly due because of its location in the peripheral area of the visual field, which corresponds to the less sensitive area.

Most effective daylighting design strategies in existing sports halls

Based on previous results, daylight design strategies were suggested for the improvement of visual comfort in four of the Olympic sports halls (Chapter 6 and Appendix IV-A). Photorealistic and calibrated images were obtained to validate the design measures proposed through experimental tests. In addition, the analysis of panel responses (Appendix IV-A and Chapter 7) reveals that users prefer a uniformly well day-lit court, when daylighting strategies were integrated. These results have shown the relevance of design strategies which effectively increase the daylighting levels and uniformity on the court, and minimize glare from windows and reflections on the floor.

Visual comfort and preferences for sports halls users

The quality analysis of panel responses (Chapter 7) shows that users prefer for playing and watching sports: a uniformly well day-lit court, an adequate contrast and absence of reflections on the court or playing area. Preference and rejection ideas resulted also consistent with test results and luminances False Colour Analysis. The court is also featured as the main and central element of the luminous space for users. The "good level of light" or the lack of light in the court was also the main factor considered for the most comfortable scenes. However, nuances and hints exposed by participants may have been lost in translation or misinterpreted. Toplighting (from the ceiling) can be considered as the preferred source of light, for maintaining the uniformity of lighting levels and focus in the court, while minimizing the risk of glare.

Luminous environment and overall perception

The combination of many factors was verified to contribute to the luminous scene perception. The most relevant for sports halls users were the horizontal illuminance level on the court, reflectance coefficients mainly on the court surfaces, colours and natural light distribution over the side walls and ceiling. However, the evaluation of users' perception showed many hints and some ambiguity about daylighting levels on the court. It was not possible to establish how much natural light is good or enough for sports halls users.

The use of saturated colours was also shown to noticeably modify the luminous space, even if lighting levels were unchanged.

Validation of daylighting design in a new sports hall: Palau d'Esports Catalunya

Daylighting design strategies were suggested and implemented in the building design of the new Palau d'Esports Catalunya, built for the Tarragona 2018 Mediterranean Games (Chapter 8 and Appendix IV-D). The goals of the optimisation of the central skylight were contrasted and verified with two Post Occupancy Evaluation campaigns, completed before and during Games. High and uniform levels of natural lighting were verified in the court in summer, with maximum values of solar radiation. As well, a low risk of visual discomfort in the central area of FOV was also corroborated. These results have shown the effectiveness of design strategies and measures implemented in the early phases of building design.

Visual comfort is affected by user position and view directions

In sports activities, the intensity and frequency of visual discomfort, disability glare and adaptation glare are strongly linked with the relative position of users into the space and their main view directions. There is a high risk of glare when users are facing sidelighting openings. In addition, frequent situations of adaptation glare are related with hard frames, backlit effect and non-uniform backgrounds or luminous patterns. This is mainly due to glare sources located in the focus and near surrounding areas of the visual field. These results suggest that multiple targets and view directions must be considered for sport users.

Daylight control and shading devices

The lack of control devices to adjust, dimmer, and remarkably to black-out natural lighting were frequent in the majority of case studies, with few exceptions of fixed blinds, screens and louvers. However, good examples of transition surfaces between glazing areas and ceilings were found. Splayed surfaces and vertical baffles were effective to avoid excessive contrasts and hard frames in toplighting systems. Many of the visual discomfort and disability glare situations found have been caused by the absence or insufficient regulation of natural light on the court. This is also the most likely cause of definitive closure of daylight openings, which can lead to the continuous use of artificial lighting.

Design and application of the methodology

As a result of this study, a specific methodology was adapted and implemented from an architectonic and holistic approach. Both qualitative and quantitative parameters of visual comfort were assessed in daylit sports halls. Objective and subjective data were collected from case studies, comprising in-situ measurements, such as horizontal and vertical illuminance. As well, high dynamic range images survey, glare and contrast analysis in the field of view, simulations, an experimental test and visual comfort surveys were carried out. In addition, the optimisation of daylight at the initial stages of the design development of a new sports facility was completed and contrasted with monitoring campaigns. These procedures have demonstrated to be useful tools to consider users' requirements and preferences in sports halls. Having these tools, different alternatives or scenarios can be considered to choose the best design strategies. In addition, the quality analysis of open-ended responses certainly contributed to the better understanding of users' preferences and visual perception in sports halls, although it was a challenging task. Likewise, this research has also shown the difficulty of the three-dimensional visual field assessment, where users and their visual targets are in movement.

Design daylighting strategies and measures guideline for natural light optimization

One of the main contributions of this research are the daylighting design strategies guidelines, which were compiled for the optimisation of natural light in sports halls of Catalonia (Appendix I). These guidelines can be useful either for retrofitting or new design of sports halls in Mediterranean climates and other climates and latitudes, since both overcast skies and clear skies were assessed. Most of these design recommendations were also suggested and implemented in the building design of a new sports hall, the Palau d'Esports Catalunya, which was promoted to be a nearly Zero Energy Building- nZEB (Appendix IV-D). As well, advances of this work resulted in conference publications (Appendix IV-C).

9.1.1 Final remarks

In spite of its limitations, this study has offered objective and subjective data about daylighting and toplighting performance in sports buildings in Mediterranean climate, from a functional and architectonic approach.

This study has found that generally toplighting is suitable for the task performance and visual comfort in sports halls, considering the quality and quantity of natural light and its distribution over the court.

The experimental test conducted has shown the feasibility and validation of different daylighting design strategies, that could be implemented in existing buildings to improve daylighting levels and visual comfort. It also emphasised the relevance of integrating design strategies at early building design phases for optimal results.

Moreover, these findings suggest that daylighting and toplighting can contribute efficiently with good levels of natural lighting and uniformity on the court, for training and competitive levels of play, including TV broadcasting requirements. This was demonstrated in the Palau d' Esports Catalunya during the realization of the 2018 Mediterranean Games.

Illuminance and luminance uniformity for sports visual tasks: short time for eye adaptation

The results indicate that the uniformity of light is a significant factor for visual tasks in sports halls. The uniformity of both horizontal illuminance levels on the court and luminances in the field of view – FOV have been verified to be essential to maintain comfortable visual conditions. This results are consistent with users' preferences, literature and best practices.

Daylighting and architectonic design: defining the luminous environment

Daylighting and architectonic surfaces have major repercussions in the indoor luminous environment, emphasising the role of the design and its impact on the users' visual perception. Floors, ceiling, side walls and fenestrations, are significantly affecting the light distribution and its balance within the space. Surfaces properties (shape, material, reflectance and colour) and their location in the users' FOV must be considered in the design process, as well the incident light by daylighting systems.

Designing with high availability of natural light: control, solar protection and black-out

Specially with natural light being abundant in Mediterranean climates, daylight control and solar protection devices are essential to maintain visual and environmental comfort. It is very important to provide a "switch-off" for daylighting, to maintain maximum natural light levels inside buildings when it is favourable but shutter-down when required.

Therefore, architectural design that does not consider effective daylight control and total black-out can cause frequent visual discomfort. This might lead to operational issues during the building's use, that could require complex technical solutions and, in the worst cases, the permanent closure of daylighting systems.

Finally, this work highlights the complexity of the design of the luminous space and encourages the inclusion of natural light from early design phases. With suitable design strategies, natural lighting can improve the environmental quality of the main space "the court". This might also contribute to energy savings by reducing operating costs for artificial lighting.

9.2 Future work

The parameters, metrics and thresholds which could affect the visual perception for visual comfort studies in buildings, have been reviewed intensely in the last few years.

This research explored a number of existing parameters and metrics that could determine the quality and quantity of natural light in sports halls (Inanici 2005b; 2010; Wienold and Christoffersen 2006; Reinhart and Mardaljevic 2006; Wienold 2009; Jakubiec and Reinhart 2012; Rockcastle and Andersen 2013; Dubois et al. 2016; Bodart et al. 2017; Pierson et al. 2018). Experimental studies and measurements were completed to explore the fulfilment of visual comfort and visual perception in top-lit sports halls with real data acquisition. Simulations were also completed to predict daylighting levels and visual comfort conditions. However, the procedures applied, conditions of measurements, simulation models, selected samples of sports buildings and survey respondents were limited.

Future research can usefully investigate and extend the scope of this work, as follows:

- in the particular case of the Palau d'Esports Catalunya, to extend Post Occupancy Evaluation - POE campaigns over the year
- the evaluation of visual comfort during sports activities may require a specific index, or adaptation or combination of existing, e.g. Daylight Glare Probability, but the eye's adaptation and absolute glare should be considered:
    - the dynamic visual task with one or multiple moving targets
    - the movement of users over the space, considering their position, and sequences of view directions
- regarding the experimental tests, simulations with clear sky and more participants might be required to have a complete validation of results:
    - numerical simulations with clear sky to verify the efficacy of design measures with sunlight or direct light
    - including a larger number of participants
    - widening users age range, including schoolchildren and adults +60 years old
    - including surveys in diverse conditions of use, training and competitions
- to consider an extensive inventory of passive and active measures, that includes:
    - advanced daylighting systems, which were not explored in this study
    - sensitivity analysis of design strategies, to weight the effectiveness in terms of visual comfort achieved and acceptance by users
- to consider other parameters that could affect users' visual perception:
    - user expectations in sports hall spaces
    - the use of colour on interior surfaces and perception, e.g. cold, warm, saturated
    - the spectrum and colour temperature of natural light
    - the influence of the visual comfort in the indoor environmental comfort
- if the daylighting design strategies suggested are still valid in other building typologies with similar space configurations and layouts, e.g. as airports, train stations, auditoriums

9.3 Myths and misconceptions of natural light in buildings

There are common "beliefs" or myths about natural lighting in buildings. These have been used as rules of thumb, but leading to possible misconceptions which may impact in the design process and visual comfort.

The repertoire of simplifications and inferences about daylighting in buildings could be used intuitively during the design process. Indeed, some of these assumptions can be useful in the early stages of building design to establish and identify main daylighting design strategies. Also, they can be used in concept design, defining the outline, orientation and shape of the space in new and retrofitting projects.

However, if these deductions are not going to be verified in the final stages of the design phases it may have further repercussions during a building's operation, which could cause frequent and persistent visual discomfort situations.

North fenestrations = diffuse light

From my experience, the most common generalization and assumption about natural light in buildings is that the light from the North (North latitude) or from the South (South latitude) is always "diffuse light" or "cold light", due the sun trajectory. Subsequent deductions associated with this are presented below:

- if fenestrations face North, they will deliver only diffuse light with no solar penetration
- thus, North fenestrations guarantee no potential glare by direct light or sunlight
- so, North fenestrations do not require daylight control and solar shading devices
- in temperate climates, toplighting must face North, to avoid solar penetration and potential thermal gains

Most of these assumptions are theoretically right, considering the solar trajectory and main requirements in terms of building orientations and most suitable daylighting systems for functional purposes. However, these are very inaccurate about other relevant factors of the visual comfort.

For example, toplighting openings facing North could result in too low daylighting levels, considering the user requirements, the visual task performance and building type.

Sunlight and glare from the North?

Specially in urban contexts, there is a high risk of discomfort and disability glare situations due to openings, especially windows facing North. These fenestrations are usually exposed to external reflected light and sunlight from opposite facing South façades. This is a frequent situation, because they are often in the opposite situation from each other.

Sun reflections in adjacent buildings, especially from light coloured façades facing South, East and West, could bring direct or indirect light trough all fenestrations, no matter their orientation, including specular reflections from exterior glazing and glossy surfaces.

Moreover, there are potential discomfort, disability glare and adaptation level situations due to the potential glare sources, totally independent from their orientation, as follows:

- the view of lighted and sun-lighted external surfaces through windows, especially when they are in the centre of the visual field or field of view - FOV
- the view of the sky through glazing areas with clear skies and especially cloudy skies (bright white/grey skies)
- excessive contrast and adaptation glare
- in the case of dynamic users, their position in the space and the main gaze directions could determine the intensity and frequency of glare. Also, it determines their position in the most sensitive areas of visual field or FOV

9.4 Epilogue: personal comments

To conclude, the functional and architectonic approach of this study aims to promote the use of natural light in this type of building, but also in others with similar layouts, offering real and simulated information. Likewise, it is to encourage designers to implement daylighting in early design stages to provide to users the benefits of natural light, while maintaining comfortable environments.

In particular, the daylighting design in intermediate latitudes, with high availability of direct and diffuse light, must be addressed with the same care and detail as in the opposite case, when it is a scarce resource.

Nevertheless, the right or minimum amount of natural light for human wellbeing is still being discussed and there are many challenges and barriers to achieve a suitable design, in buildings and urban contexts. Thus, existing standards and regulations must be adapted to appropriate natural lighting design guidelines.

Importantly as well, is to offer good quality of indoor environmental comfort, considering that we spend most of our time indoors. Unfortunately, this situation has gained an exceptional dimension during this year 2020, because of the sanitary crisis declared around the word. During this emergency, deep plan layout buildings such as sports buildings have demonstrated to be highly valuable spaces to respond to unprecedented demand. It was not specifically for the purpose for which they were designed, but for other essential functions, such as hospitals, schools, and shelter or short-accommodation. A good example of this is the Institut Nacional d'Educació Física de Catalunya - INEFC in Barcelona, which was reconditioned to run as an extension of the Hospital Clinic de Barcelona for treatment of Covid-19 patients.

In spite of all the challenges described, as designers, we must secure good quality and quantity of natural light both indoors and outdoors spaces. Thus, the implementation of natural light in the design process should be out of the question. Basically, good practices should consider solar protection, control and black-out from early design concept.

Therefore, comprehensive and more creative design approaches must be considered to guarantee right amounts of daylighting and to benefit from its dynamic qualities, to maintain our vital link with nature, as well our health, good mood and wellbeing. After all, the rhythms of natural light-darkness, day-night are one of main characteristics we share with all the rest of living species.

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GLOSSARY

Activity area: area within which a specific activity is carried out.

Adaptation: the process which takes place as the visual system adjusts itself to the brightness or the colour of the visual field.

Background area: area or region adjacent to the immediate surrounding task area within the visual field.

Brightness: the subjective response to luminance in the field of view dependent upon the adaptation of the eye.

Colour rendering index (CRI): index designed to express synthetically a quantitative evaluation of the differences in colour between eight test colours lit directly by the standard illuminant D65 and by the same illuminance transmitted through the window, shading device or electric lighting system.

Contrast: subjectively the difference in appearance (brightness or colour or both) of two parts of a visual field seen simultaneously or successively. Objectively, the luminance difference between the two parts of the field.

Court: an area drawn out on the ground that is used for playing sports such as tennis and basketball.

Daylight Autonomy: is a daylight availability metric that corresponds to the percentage of the occupied time when the target illuminance at a point in a space is met by daylight. The calculation is based in annual data and lighting levels.

Daylight Factor: the illuminance received at a point indoors, from a sky of known or assumed luminance distribution expressed as a percentage of the horizontal illuminance outdoors from an unobstructed hemisphere of the same sky. Direct sunlight is excluded.

Daylight or Natural light: the combined effect of sunlight and skylight.

Daylighting: daylighting refers to the different approach and the layers of the fenestration placed in buildings to bring natural light to indoors. These layers compose the daylighting systems.

Diffuse lighting: lighting in which the luminous flux comes from many directions, none of which predominates.

Disability glare: glare produced directly or by reflection that impairs the vision of objects without necessarily causing discomfort.

Discomfort glare: glare that causes discomfort without necessarily impairing the vision of objects. Discomfort glare may be produced directly or by reflection.

Field of play: general term for the defined space in which the sports activity takes place.

FOV - Field of View: the part of space which can be seen by the observer, at any given moment.

Foveal or Focus area: is the seeing of objects in the fovea, which is approximately he 2° in the central part of the visual field

Glare: excessive brightness in the visual field. The discomfort or impairment of vision experienced when parts of the visual field are excessively bright in relation to the general surroundings.

HDRI - High Dynamic Range Image: technique used in digital photographic imagining and ray-traced computer simulations to reproduce a greater dynamic range of luminosity.

Illuminance: the luminous flux density at a surface, i.e. The luminous flux incident per unit area.

Immediate surrounding area: band or region surrounding the task area within the visual field.

Luminance: a measure of the stimulus which produces a sensation of brightness measured by the luminous intensity of the light emitted or reflected in a given direction from a surface element, divided by the projected area of the element in the same direction. It is typically expressed in cd/m².

Peripheral area: is the seeing of objects displaced from the primary line of sight and outside the central visual field.

Reflectance or Reflection factor: the ratio of the luminous flux reflected from a surface to that incident on it.

Rooflight or roof light: is a window placed in a roof or ceiling to naturally lit indoors or skylight.

Sidelighting: strategies to day lit indoors from windows placed in side, or light coming from the side.

Skylight: the diffuse light from the sky vault, excluding direct sunlight. See also rooflight definition.

Sunlight: the direct light from the sun, after diffusion in the atmosphere.

Task area: area within which the visual task (computer, paper based or other) is carried out.

Toplighting: strategies to day lit indoors from windows or openings placed in the top or roof, or light coming from the top.

Transmittance: ratio of luminous flux transmitted by a material, such as a window, to the incident luminous flux.

Uniformity: the evenness of the distribution of light over the court surface. There are two definitions of Uniformity, known as U1 (ratio of E_{min}/E_{max}) and U2 (ratio of E_{min}/E_{ave}).

Visual field: see Field of View.

Visual task: an activity which requires the visual perception of the observer, in a specific area or visual task area.

Working plane: the plane in which the visual task lies. If no information is available, in the case of sports halls, the working plane may be considered to be horizontal and at floor level.

Units and symbols

E Illuminance (lux)

E_{hg} Exterior horizontal global illuminance (lux)

$E_{surround\ task}$ Horizontal illuminance surrounding the task (lux)

E_{task} Horizontal illuminance on task (lux)

$E_{vertical\ eye}$ Vertical illuminance on the eye (lux)

E_{vgs} Vertical sky illuminance on façade (lux)

E_{wp} Horizontal illuminance at work plane height (lux)

L_b Background luminance (cd/m^2)

$L_{ceiling}$ Luminance of the ceiling (cd/m^2)

L_s Luminance of a glare source (cd/m2)

L_{task} Luminance of task (cd/m^2)

Lux Unit of illuminance, equal to one lumen per square metre (lm/m^2).

L_{walls} Luminance of the walls (cd/m^2)

P Guth's position index

ρ Reflectance

$\tau_{v,\ n\text{-}dif}$ Diffuse part of light transmittance

$\tau_{v,\ n\text{-}n}$ Normal/normal transmittance

ω or ω_s Angular size of a glare source (sr)

Sports halls buildings acronyms

CEM EI:	Centre Esportiu Municipal L'Espanya Industrial, Barcelona
CEM LV:	Centre Esportiu Municipal La Verneda-, Barcelona
CEM VH:	Centre Esportiu Municipal Vall d'Hebron, Barcelona
CEM RCR:	Centre Esportiu Municipal del Raval Can Ricart, Barcelona
CE CCE:	Complex Esportiu del Consell Català de l'Esport, Esplugues de Llobregat
INEFC:	Institut Nacional d'Educació Física de Catalunya Montjuïc, Barcelona
PBFCB:	Palau Blaugrana Futbol Club Barcelona, Barcelona
PMEB:	Palau Municipal d'Esports de Badalona, Badalona
PSJ:	Barcelona Palau Sant Jordi, Barcelona
PEG:	Palau d'Esports de Granollers, Granollers
PPMB:	Pavelló Poliesportiu Municipal de Banyoles, Banyoles
PMGF:	Pavelló Municipal de Girona Fontajau, Girona
PMVA:	Poliesportiu Municipal Virrei Amat, Barcelona

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